# ESTIMATING CARBON STOCKS IN TREE BIOMASS AND SOILS UNDER ROTATIONAL WOODLOTS AND NGITILI SYSTEMS IN NORTHWESTERN TANZANIA

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By

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**ABSTRACT**

Woodlot and natural woodland systems in the semi-arid regions in Tanzania are believed to have a high potential to sequester carbon (C) in their biomass and the soil which may qualify for C credits under the current voluntary C market schemes like, the REDD program. However, our understanding of the processes influencing storage and dynamics of C in soils under semi-arid agroforestry systems such as these woodlot systems is limited. This study evaluated C pools in soil and tree biomass in woodlot species of *Albizia lebbeck, Leucaena leucocephala, Melia azedarach*, and *Gmelina arborea*; and in farmland and *ngitili* systems. Synchrotron-based C K-edge x-ray absorption near-edge structure (XANES) spectroscopy was also used to study the influence of these land use systems on the soil organic matter (SOM) chemistry to understand the mechanisms of soil C changes. Soil samples were collected to 1 m depth and subsamples for each land use system to 0.4 m depth were fractionated into macroaggregates (2000-250 μm), microaggregates (250-53 μm), and silt and clay-sized aggregates (<53 μm) to provide information of C dynamics and stabilization in various land uses. SOC was analyzed in whole and soil aggregates and biomass C was estimated using developed biomass models from the literatures. Aboveground biomass carbon in the woodlots from the Kahama district ranged from 11.76 Mg C ha$^{-1}$ to 24.40 Mg C ha$^{-1}$. Based on the age of woodlots and the rate of carbon sequestration potential (CSP), *Gmelina arborea* had the highest rate of aboveground C sequestration (3.59 Mg C ha$^{-1}$ year$^{-1}$). The SOC stocks in whole soil for the land use systems from the two districts ranged from 43-67 Mg C ha$^{-1}$. The degraded ngitili did not show a reduction in SOC stocks despite reducing aboveground biomass C stocks by 15.11 Mg C ha$^{-1}$. SOC in the woodlots were found to be associated more with the micro and silt-and clay-sized aggregates than the macroaggregates, reflecting high stability of SOC in the woodlot systems. The XANES C K-edge spectra revealed the stabilization of recalcitrant aromatic C compounds in the silt and clay-sized aggregates. This study demonstrates the significant contributions of woodlots in biomass C accumulation as well as long-term SOC stabilization in soil fractions. Thus, these agroforestry practices hold promise to meet household energy needs while contributing to climate change mitigation and adaption.

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# 1. INTRODUCTION

## 1.1. Background

There has been an increased need for forest dependent-people with limited economic opportunities in developing countries to expand agricultural activities to meet the demand of increasing population growth. This has intensified the depletion of natural forests causing deforestation and increased emissions of greenhouse gases (GHGs) such as carbon (C) (Kimaro et al., 2011). Land use changes such as afforestation and deforestation can have major impacts on C storage and global warming (CRS, 2007). Loss of tropical forests is estimated to contribute 20-25% of C emissions annually (IPCC, 2007). This indicates the importance of forests in the global C cycle and climate change.

The introduction of programs such as the United Nation's collaborative program on reducing emissions from deforestation and degradation (UN-REDD) in developing countries is believed to be an incentive to promote forest conservation (Moutinho et al., 2005). The UN-REDD is a program that is being introduced to allow countries to be rewarded for reduced deforestation by providing financial incentives through an international C market (Kimaro et al., 2011). However, since agricultural production is another major source of GHG emissions, accounting for deforestation and forest depletion alone may not reduce C emissions effectively in developing countries (van Noordwijk et al., 2008; Kimaro et al., 2011). As a result, comprehensive C trading schemes that promote emission reductions in Agriculture, Forestry and Other Land use (AFOLU) sectors are also being developed (Negra and Ashton, 2009; Kimaro et al., 2011). These C trading schemes have focused mainly on biomass C despite the enormous contribution of soils in C sequestration. Soils are known to contain more C than the vegetation and atmosphere combined (Lal, 2004) which has raised concerns to broaden the scope of C markets to include soil C (FAO, 2008).

Soil organic matter (SOM) is the largest reservoir of organic carbon (OC) in the soil (Schlesinger, 1995). Soil organic matter exists in different forms and at various stages of decomposition in the soil along with variable turnover rates which means that not all C in the soil can be considered sequestered (Montagnini and Nair 2004; Nair et al., 2010). Depending on environmental conditions and land use change, the soil may act as a source or sink of C (Marschner et al., 2008). Soil organic matter stabilization, which promotes long-term C storage, is enhanced by the molecular characteristics of the organic matter and its association with soil aggregates (Sollins et al. 1996). Unlike studies in soil C storage, interests in litter quality in soil fertility studies have always focused on the ability of plant litter to readily release nutrients through mineralization. Residue quality indices such as carbon to nitrogen (C/N) ratios and nitrogen (N) have often been used as an index to assess the quality of plant litter. Conversely, low quality litters indicated by high C/N ratios have been observed to result in SOM accumulation and decreased SOM degradation rates (Solomon et al., 2000). The tendency of soil to store C for longer periods is also influenced by the nature of the soil aggregates (Takimoto et al., 2009). This could range from short-term storage in macroaggregates (>250 μm diameter) to long-term storage of C in the silt and clay size fraction (<53 μm) (Six et al. 2002). The interaction of SOM with soil aggregates has been observed to reduce SOM decomposition by: forming a physical barrier between microorganisms, microbial enzymes, and their substrates; controlling food web interactions; and influencing microbial turnover (Nair et al., 2010). This makes it very crucial for soil C sequestration studies to take into consideration not only the quantity but also the form of the C stored and the soil size fractions, which are associated with the stored C. This information will give insight into the long-term stability of the stored C and its contribution to the global climate change.

Agroforestry systems, which involve the incorporation of trees to agricultural lands, have received international recognition not only as a means of restoring degraded lands but also for their contribution to atmospheric C sequestration (Lal, 2003; Nair, 2011). Trees, therefore, play an important role in sequestering C in both above and belowground biomass (Nair et al., 2009). This potential has prompted several studies to evaluate the C sequestration potentials of different agroforestry and other tree-based system for different ecological regions (Nair et al., 2011). Consequently, rotational woodlots (an agroforestry technology), which were established in Tanzania purposely to supply on-farm fuelwood to reduce the high rate of deforestation, and ngitili systems have also been recognized as potential C sequesters (Kimaro et al., 2007b). 'Ngitili' is a vernacular term, which describes a traditional method of natural regeneration that involves management of natural vegetation and woodlands for fodder (Nyandzi et al., 2003; Zahabu and Otsyina, 2010). Studies in these woodlots and ngitili systems to evaluate their C sequestration potentials have not been exploited extensively. The few studies in these systems to evaluate their soil C sequestration potentials have focused in the upper soil layers whereas the few biomass C estimations in the woodlots have not covered the majority of the different woodlot species. Moreover, soil C studies in these systems have not included the different forms of C that are associated with different soil aggregate fractions. Therefore, this study sought to estimate the aboveground and soil C stocks in some selected woodlots species and ngitili systems in the Shinyanga region, Tanzania. The specific objectives were to 1) estimate the biomass carbon stocks in planted woodlots and ngitli systems in Shinyanga, 2) determine the soil carbon stocks in bulk soil and soil fractions under planted woodlots, ngitili systems and farmlands in Shinyanga, and 3) evaluate the changes in SOM chemistry and different carbon forms in macro-sized and silt and clay-sized soil fractions in planted woodlots, ngitili systems, and farmlands in Shinyanga.

### 1.2. Hypotheses

The hypotheses to be tested for each objective in this study are 1) planted woodlots have similar levels of biomass carbon and SOC as those in the ngitili systems, 2) tree-based systems have higher SOC contents in the bulk and smaller sized fractions than the farmland, and 3) soil organic matter chemistry differs with soil sized fractions and land use systems.

### 1.3. Organization of the thesis

The research in this thesis is organized in a manuscript format. Chapter 2 reviews the literature on how increases in the atmospheric $CO_2$ concentrations have led to global warming and the recognition of terrestrial C sequestration in vegetation and soil as a means of possible climate change mitigation strategy. The mechanisms involved in soil organic matter stabilization and how these processes affect soil carbon sequestration have also been reviewed in this chapter. Concluding the literature review chapter is a review on how agroforestry and other land use systems in the semiarid regions in Tanzania and neighbouring countries affect soil carbon stocks. Chapter 3 and 4 present the studies that were carried out in this research. Chapter 3 presents a study on estimating biomass carbon in woodlot species of *Albizia lebbeck*, *Leucaena leucocephala*, *Melia azedarach*, and *Gmelina arborea* and in natural woodlands (ngitilis) using developed biomass equations from the literature. The soil organic carbon contents in whole soil and soil fractions to 1 m depth in these land use systems as well as in farmland is presented in chapter 4. In addition to the soil organic carbon contents estimation in whole and fractionated soils in chapter 4, the results of C K-edge XANES spectroscopy to assess the impact of these land use changes on the chemistry of soil organic matter and the different forms of carbon in macroaggregates fractions and silt and clay fractions is presented. The synthesis and conclusion of the research chapters as well as future research opportunities is presented in chapter 5.

# 2. LITERATURE REVIEW

## 2.1. Carbon and global warming

Increases in the concentrations of greenhouse gases (GHGs) comprising carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and halocarbons in the atmosphere are now higher than before the industrial revolution (IPCC, 2007). Human activities such as land use changes and industrialization have resulted in these increases causing a change in the earth's climate (Lal, 2003). Among these GHGs, $CO_2$ is the most voluminous produced by humans (CRS, 2009). The voluminous amounts of $CO_2$ emitted to the atmosphere and their greenhouse effects implication has resulted in widespread concerns to reduce the concentrations of $CO_2$ emissions in order to mitigate their global warming (CRS, 2007).

The advancement of industrialization in developing countries for economic growth increases the likelihood of more global energy consumption associated with carbon (C) emissions (PwC, 2008). Dlugokencky and Tans (2014) estimate the global $CO_2$ level in 2013 at 395.92 ppm compared to the concentration before the industrial revolution, which was estimated at 280 ppm (Battin et al., 2009). The 2013 atmospheric $CO_2$ concentration represents a 41 % increase over the concentration before the industrial revolution. Emissions resulting from industrialization particularly, fossil fuel burning and cement production were estimated at $5.4 \pm 0.3$ Pg C $yr^{-1}$ and $6.3 \pm 0.4$ Pg C $yr^{-1}$ during the 1980s and 1990s, respectively (IPCC, 2000). Approximately, about 270 (±30) Pg C were emitted as $CO_2$ into the atmosphere from fossil fuel combustion and cement production between 1857 and 1999 (Lal, 2003).

Projections by PwC (2008) showed that if industrialized countries continued with their emissions without solutions to reduce these emissions from the atmosphere into permanent sinks, that global C emissions could more than double by 2050. These projections could possibly have severe longer-term repercussions on global warming and related climate change.

The process of removing C from the atmosphere and storing it in a reservoir is one of the approaches to reducing $CO_2$ concentrations in the atmosphere and thus possible climate change mitigation (Nair et al., 2009). The natural process of capturing and storing C in terrestrial ecosystems has been considered as a cost-effective approach for carbon sequestration, which comes with numerous added benefits (Kimaro et al., 2011). The terrestrial C is estimated at 2000 $\pm$ 500 Pg representing 25% of global C stocks (Albrecht and Kandji, 2003). As a result, terrestrial C sequestration in vegetation and soil has been recognized as a means of mitigating high atmospheric concentrations of $CO_2$ that causes global warming (Saha et al., 2010). This makes vegetation and soils an important component in C sequestration and climate change mitigation, underscoring the need to understand the role played by the soil and vegetation in C sequestration.

**2.2. Vegetation (aboveground) carbon sequestration**

Terrestrial vegetation is estimated to contain 550 $\pm$ 100 Pg C (Houghton, 2007). Carbon sequestration in plant biomass is facilitated when atmospheric $CO_2$ is incorporated into plant tissues through photosynthesis for biomass production (CRS, 2007). As trees grow, more photosynthesis occurs which converts more of the $CO_2$ in the atmosphere into the biomass of the trees, reducing the atmospheric carbon and sequestering it in their tissues (CRS, 2009). The aboveground C in vegetation differs with type of production system and ecological region within which a system is practiced (Nair et al., 2010).

Nair et al. (2009) reports that the aboveground C sequestration potentials in different agroforestry systems from different ecological regions range from 0.29 to 15.21 Mg $ha^{-1}$ $year^{-1}$. The variable range for these systems was explained by Nair et al. (2010) to depend on factors such as the land use type, site characteristics, species involved in the system, stand age, and the management practices. Similar to the agroforestry systems in the arid, semiarid, and degraded sites having lower C sequestration potentials than fertile humid sites, temperate agroforestry systems have also been indicated to have lower C sequestration potential compared to the tropical agroforestry systems (Nair et al., 2010).

The global forest biomass in 2005 was estimated to contain a total of 283 Pg C (Funder, 2009). Recent studies have indicated that 18 % of $CO_2$ emissions from fossil fuel combustion are captured by primary forests (forests which have never been cultivated or harvested) (Lewis et al., 2009). The IPCC (2007) estimated that for primary forests that 65 % of their mitigation potential is found in the tropics. Estimates of biomass C storage are often based on the assumption that, 50 % of oven-dry weight of stem and branches constitute C, although this assumption has been challenged (Nair, 2011). Different methods of biomass C estimation have been developed including direct field measurements, conventional forest inventories, growth and yield modeling, and remote sensing (Mugasha et al., 2012).

### 2.3. Aboveground carbon estimation

Considering that reliable biomass estimates are required to accurately measure and monitor C pools and fluxes in trees, collection of credible tree biomass data is needed. The scarcity of credible tree data has been attributed to the use of unreliable biomass estimation techniques (IPCC, 2003; Kaonga and Bayliss-Smith, 2009). Cutting and weighing tree biomass in the field is regarded as the most accurate method to estimate aboveground tree biomass (Ketterings et al., 2001; Kaonga and Bayliss-Smith, 2009). However, this procedure is complex, time consuming, destructive and labour intensive which restrict its use to small areas and small tree sample sizes (Ketterings et al., 2001; Delitti et al., 2006; Kaonga and Bayliss-Smith, 2009). As a result, regression models that relate biomass growth parameters such as total tree height and basal diameter have been developed to estimate aboveground biomass.

The architecture and wood density of trees differ from individual species and as a result, the use of species-specific equations has been preferred in developing allometric equations (Ketterings et al., 2001). Conversely, the presence of different tree species existing in the same area means that enormous efforts will be needed to develop species-specific equations. Therefore, generalized biomass equations have often been used for biomass C estimation purposes (Chave et al., 2005). In the use of generalized biomass equations, there is the need to take into account the ecological characteristics of the site. Mugasha et al. (2012) developed site specific, miombo categories (dry and wet), and generalized biomass equations for miombo woodlands in Tanzania. They indicated that the generalized models could be applied to other miombo woodlands with similar conditions as the study site. However, they concluded that for improved biomass estimates of study sites, preference should be given to the site-specific biomass models over the general biomass model showing the need to consider ecological characteristics in the use of biomass models for C estimations.

With regards to C stored in biomass, concerns have been raised about the longevity of the stored C. Despite the enormous amounts of atmospheric $CO_2$ that is captured into vegetation biomass, the amount of biomass C that is considered sequestered depends on factors such as species, plant part, and ecological conditions (Nair, 2011). In addition to the C stored in tree biomass, carbon is also sequestered in the soil when the aboveground parts of the trees such as the leaves and branches or belowground roots die and partially decompose into humus (CRS, 2007).

### 2.4. Belowground (soil) carbon sequestration

Globally, soil contains the largest pool of actively cycling C in terrestrial ecosystems. The soil is estimated to contain 1500-2000 Pg C to 1 m depth (Janzen, 2004). Soil organic matter (SOM), which is composed of plant, animal and microbial residues in various stages of decay, is a major reservoir of soil organic carbon (SOC) (Janzen, 2004; Helfrich et al., 2006; Saha et al., 2010). Plant biomass, which contains C in sugars, starch and cellulose, are returned and kept in the soil as partially decomposed litter. The amount of C stored in the soil is controlled by the balance between inputs from net primary productivity (NPP) and decomposition rates (Janzen, 2004). The balance between organic matter (OM) inputs and decomposition rate is influenced by the quantity and quality of the OM (von Lutzow et al., 2006), which in turn affects the long-term accumulation of SOM for C sequestration (Helfrich et al., 2006).

Von Lutzow et al. (2006) outlines three phases of SOM decomposition. The first phase of decomposition is associated with the labile or active SOM pools with a turnover time of about 1-2 years. A loss of about a quarter to two-thirds of the initial C is reported for this phase of SOM decomposition in temperate climates (von Lutzow et al., 2006). The next phase of slow decomposition occurs in the intermediate SOM pools, which have a turnover time of about 10-100 years. This phase of decomposition results in the loss of about 90% of the OM in total. The third and final phase has a very slow decomposition rate, which completes the decay process. This phase of decomposition is associated with the recalcitrant SOM pool and takes longer with a turnover time of about 100-1000 years. The recalcitrant SOM pool is responsible for the long-term stabilization of carbon in soils (Helfrich et al., 2006). The return of biomass to the soil in excess of decomposition also enhances the preservation of the recalcitrant OM pools from decomposition (Helfrich et al., 2006).

Decreases in SOC pools as a result of reduced litter inputs have been reported in different ecological systems. Lal. (2003) observed a loss of 30-50 Mg C $ha^{-1}$ in SOC pools in agricultural soils which was attributed to low quantity biomass returned to the soils and increased decomposition rate. Takimoto et al. (2009) also found a relatively lower SOC in agricultural and agroforestry systems in the West African Sahel region. The soils had carbon contents of less than 6 g C $kg^{-1}$ soil which they attributed to the rapid decomposition of OM; however, Batjes (2004) indicated that best management practices on these agricultural soils aimed at conserving SOM have the potential to increase their carbon sequestration in the range of 0.2-0.4 Mg C $ha^{-1}year^{-1}$. Gama-Rodrigues et al. (2010) evaluated C storage under cacao agroforestry systems in Brazil and observed high amounts of soil C, which they attributed to the deposition of higher amounts of plant litter. After a 5-year fallow period, Kimaro et al. (2011) also observed organic carbon (OC) in the top 0-15 cm soil depth under three *Acacia* tree species (A. *nilotica*, A. *polyacantha*, and A. *mangium*) ranged from 21.6-25.6 Mg C $ha^{-1}$ compared to 13 Mg C $ha^{-1}$ in a continuously cropped soil. They concluded that the rapid enrichment of SOC in the tree fallow systems was due to high additions of OM. Bronick and Lal (2005) also suggested that the development of SOM conservation practices in agricultural systems such as no tillage, incorporation of trees, and continuous input of OM improved soil aggregation and soil C accumulation. This partly explains the findings by Duiker and Lal (1999) where they found a linear increase in SOC pool with an increase in mulch rate. This means that the importance of long-term stabilization of SOM and the mechanisms involved in this process cannot be overlooked if the soil is to play a role in C sequestration.

### 2.5. Soil organic matter stabilization in soils.

Soil organic matter stabilization is very crucial in soil C storage. With SOM constituting the largest reservoir of OC in the soil, any change in the size and the turnover rate of SOM may potentially alter the soil C pool as well as the atmospheric $CO_2$ concentration (von Lutzow et al., 2006). Biochemical recalcitrance, physical protection, and chemical stabilization (organomineral interaction) have been identified as the three main processes that are involved in SOM stabilization (von Lutzow et al., 2008).

### 2.5.1. Biochemical recalcitrance of soil organic matter

The biochemical recalcitrance of SOM stabilization is facilitated by the complex chemical composition of the OM (Krull et al., 2003). Plant residues are composed of complex mixtures of organic compounds, which vary in their degradability (von Lutzow et al., 2006). Recalcitrant compounds such as aromatic humified components and wax-derived long chain aliphatics, lignin, and polyphenols are more resistant to microbial degradation (von Lutzow et al., 2006). Polysaccharides, whose C content in soils are estimated by the height of the O-alkyl region in solid-state $^{13}C$-NMR measurements are considered to be more labile to decomposition (Krull et al., 2003). Carbon in the recalcitrant compounds are considered to constitute very stable forms of SOC due to their resistance to microbial attack (Krull et al., 2003).

Lorenzo and Lal (2005) indicated that the biochemical recalcitrance of SOM can either be due to the inherent property of the plant litter containing recalcitrant compounds like lignin, tannin, cutin, and suberin or due to stable aromatic and long chain aliphatic compounds which accumulate during decomposition. Von Lutzow et al. (2006) categorized the biochemical recalcitrance of SOM into the primary recalcitrance of plant litter and rhizodeposits, which is a function of their inherent molecular and the secondary recalcitrance of microbial products, humic polymers, and charred organic matter.

Contradictory findings exist in the literature with regards to the mechanisms involved in the long-term stabilization of SOM. Krull et al. (2003) argued in their work that though, organo-mineral interactions (chemical stabilization) and spatial inaccessibility (physical protection) can slow decomposition processes, the molecular recalcitrance appears to be the only mechanism for long-term SOM stabilization. This contradicts the assertion by von Lutzow et al. (2006) that the soil biotic community is able to decompose any OM of natural origin and therefore, molecular recalcitrance is only important during the early stages of decomposition and in active surface soils and less relevant during late decomposition and in subsoil. These findings led von Lutzow et al. (2008) to conclude that the potential stabilization of SOM in the long-term is site and horizon-specific.

### 2.5.2. Physical protection of soil organic matter

Physical mechanisms such as OM burial within aggregates of mineral particles enhance SOM stabilization (Krull et al., 2003; Lorenzo and Lal, 2005; von Lutzow 2006). Soil aggregates form physical barriers that physically protect SOM and reduces its accessibility for microbial degradation (Six et al., 2002). Von Lutzow et al. (2006) outlined that; occlusion of OM by aggregation, intercalation of OM within phyllosilicates, hydrophobicity of OM, and encapsulation of OM in organic macromolecules are the important processes that have the potential of reducing the accessibility of SOM to decomposition. These processes protect the SOM from decomposition due to reduced access to microorganisms and their enzymes, reduced diffusion of enzymes into the intra-aggregate space of the soil matrix, and reduced diffusion of oxygen restricting aerobic decomposition (von Lutzow et al., 2006). These processes involved in the physical protection of the OM ensure that labile SOM fractions remain in the soil for longer periods of time (Six et al., 2002).

### 2.5.3. Chemical stabilization of soil organic matter

The adsorption of SOM on mineral surfaces to form organomineral complexes with cations has been identified to stabilize SOM. The majority of recalcitrant SOM have been found to be associated with mineral surfaces. A study by Solomon et al. (2000) in northern Tanzania observed that organomineral protected SOM in the silt and clay fractions were the least influenced by cultivation reiterating the importance of organomineral stabilization of SOM in soils of semi-arid tropics. In another study, Mikutta et al. (2006) also found that at least 86 % of SOM in acid forest subsoils were protected through organomineral interactions. The extent of organomineral interactions has been observed to increase with decreasing particle size and the presence of multivalent cations in the cation exchange complex (Baldock et al., 2004). Positive correlations have been found by several studies for the amount of OC in soils with clay content (Solomon et al., 2000; Lehmann, 2001; Saha et al., 2010). Six et al. (2002) explained that, the type of clay (1:1 and 2:1 clays) plays an important role in SOM stabilization. This is due to the differences in their surface area and the cation exchange capacity (CEC), which affect adsorption of organic materials to their surfaces. Contrasting effects of Fe- and Al-oxides on SOM stabilization have been examined to either reduce the available soil mineral surface for adsorption of SOM or co-flocculate SOM and consequently stabilize it (Six et al., 2002; Lorenzo and Lal, 2005).

## 2.6. Aggregates stabilization of soil organic matter

Soil aggregates, formed by the interaction of mineral particles and binding agents (organic and inorganic) are known to greatly influence SOM decomposition and stabilization (Six et al., 2002). This is because, the interaction of SOM with soil aggregates has been observed to reduce SOM decomposition by: forming a physical barrier between microorganisms, microbial enzymes, and their substrates; controlling food web interactions; and influencing microbial turnover (Nair et al., 2010). Depending on diameter, soil aggregates are classified into macroaggregates (250-2000 μm diameter), microaggregates (53-250 μm diameter), and silt and clay fractions (<53 μm). Soil organic carbon associated with macroaggregates is considered the least stable, followed by the intermediate sized microaggregates, with the silt and clay fractions being the most stable (Nair et al., 2010). The age and size of C differs with the nature of the aggregate classes in which the C is located (Nair et al., 2010). Tisdall and Oades (1982) developed an aggregate hierarchy model where they explained that in soils where the major binding agents for aggregate formation are organic matter such as in temperate soils, SOC is expected to be higher in macroaggregates than in microaggregates and the silt and clay fractions. A study by Gama-Rodrigues et al. (2010) in cacao agroforestry systems in Brazil indicated that the macroaggregates, microaggregates, and silt and clay fractions had 72, 20, and 8 % of SOC, respectively. Nair et al. (2010) indicated that the C in the macroaggregates represent the recently deposited C in the soil and are considered the labile C pools which are mostly susceptible to decomposition. Saha et al. (2010) explained that these C pools in the macroaggregates class are those that are much influenced by land-use and soil management followed by microaggregates with the silt and clay fractions being the least influenced.

However, in oxide rich soils such as Oxisols, oxides rather than SOM have been indicated to dominate as binding agents for aggregate formation (Six et al., 2004). In such soils, Gama-Rodrigues et al. (2011) noted that SOC would not be expected to dominate in the largest aggregate class as occurs in temperate soils where organic matter dominates as binding agents for aggregate formation (Six et al., 2004). Changes in land use and soil management systems have been observed to influence not only the quantity, but also the quality and stability of SOM. This makes it imperative to consider the effect land use changes have on SOC storage and its stability.

### 2.7. Effects of land use changes on soil organic matter chemistry and stabilization

Recent changes in land use which include clearing of forests, cultivation of forest and grassland soils, and creation of pastures for grazing have been found to be most pronounced in tropical countries (Davidson and Ackerman, 1993). The continuous cultivation of soil does not only have an influence on the quantity of SOM but also on its quality and stability (FAO, 2001). Tillage practices cause reductions in SOM by exposing buried OM to erosion and mineralization. This results in the loss of SOM pools that are susceptible to microbial degradation. Helfrich et al. (2006) referred to these fractions as labile OM pools which Shrestha et al. (2008) observed to have been reduced by 50% within the surface layer depth (0-20 cm) of an old cultivated soil compared to a forest soil in a study they carried out in Nepal. Solomon et al. (2000) also observed that clearing and cultivation of a native tropical woodland in northern Tanzania resulted in a decline in SOM contents in all soil size fractions. Within the first 3 years of cultivation, the SOM pool that was associated with the larger soil fractions, defined as the labile pools showed a rapid decline.

The chemistry of SOM which influences its stability in the soil is also known to be affected by land use changes. Studies by Helfrich et al. (2006) to assess the effect of land use on the composition of SOM in forest and grassland soils observed that aggregates of the forest soil had a greater proportion of alkyl-C than O-alkyl-C compared to the grassland soil. They attributed these findings to the quality of litter and the accumulation of less decomposed particulate organic matter (POM) in the forest soil. They again noticed a higher aromaticity of the SOM in a cultivated soil than in the forest soil despite the plant litter in the forest having a higher content of aromatic C than that in the cultivated soil. They concluded that microbial degradation in the cultivated soil led to the selective preservation, which resulted in the accumulation of recalcitrant SOM pools with aromatic C in the cultivated soil. This finding agrees with Solomon et al. (2005) where they observed that a native forest in Kenya dominated in easily degradable SOM constituents such as polysaccharides-C and labile components of aliphatic-C whereas aromatic and recalcitrant forms of aliphatic-C were dominant in the cultivated soil.

### 2.8. Impact of agroforestry and other land uses on soil carbon stocks

The use of afforestation and reforestation to offset $CO_2$ emissions has resulted in the recognition of agroforestry as a land use system to capture and store atmospheric $CO_2$ in plants and the soil (Nair, 2011). From the C cycle and global C emissions perspective, agroforestry is of interest for two major reasons. The first reason is the ability of the tree components to fix and store C in both biomass and the soil. The second reason for interest in agroforestry is its potential to reduce deforestation by addressing most of the drivers of deforestation and forest degradation (Kimaro et al., 2011).

Assessment of C storage in different ecological-regions was carried out by Schroeder (1994) where it was observed that in tropical areas, C storage of 21 Mg C $ha^{-1}$ in sub-humid to 50 Mg C $ha^{-1}$ in the humids can be obtained from agroforestry with cutting cycles of 5 or 8 years which is far shorter than for native forests. Studies by Kimaro et al. (2011) on C pools in a 5-year rotational woodlot system also found that the carbon storage potential of *Acacia* tree species used in agroforestry systems, yielded 18-26 Mg C $ha^{-1}$ which were similar to miombo forest reserves in the semiarids. They concluded that it will take 4-9 years for these agroforestry systems to recover the C lost through forest clearance compared to 2-3 decades for re-growing miombo woodlands. The IPCC (2000) also estimated that the conversion of unproductive croplands, which are widespread in the sub-humid areas of tropical Africa, would permit tripling of the C stocks from 23-70 Mg $ha^{-1}$ over a 25-year period. The enormous potential of agroforestry to offset $CO_2$ led Wright et al. (2001) to suggest that agroforestry would be the only land use system that could be implemented to mitigate the atmospheric $CO_2$ through terrestrial C sequestration.

Soil C stocks in different land use systems in the miombo woodlands in the semiarid regions of Tanzania and neighbouring countries have been reported. In Mozambique, Williams et al. (2008) found that SOC stocks in the upper 30 cm depth of abandoned agricultural land had 21-74 Mg C $ha^{-1}$ and 18-140 Mg C $ha^{-1}$ in miombo woodlands. Though they observed a median C stock of 23 % lower in the abandoned agricultural lands than the surrounding woodlands, no significant difference was observed between the pooled soil C stocks in the abandoned lands and the woodlands. They explained that selection of more fertile soils for cultivation by farmers could have led to the less possibility of high SOC depletion in the cultivated soils to levels lower than those in the woodlands. Williams et al. (2008) again observed that after 20-30 years of abandonment, soil C accumulation in the abandoned lands was not significant suggesting a slow rate of SOM accumulation in these soils. Walker and Desanker (2004) on the other hand observed a

40 % reduction in C after the conversion of natural miombo woodland in Malawi to agricultural land whereas a reduction of 56 % SOC was observed in Tanzania after 15 years of cultivating natural woodland to agricultural land (Solomon et al., 2000).

# 3. ESTIMATION OF BIOMASS CARBON IN PLANTED WOODLOTS AND NGITILI SYSTEMS IN SHINYANGA, TANZANIA.

## 3.1. Preface

The recognition of woodlot systems in Tanzania as potential C sequesters is due to the enormous amounts of C different agroforestry systems have been observed to contain. Carbon sequestration in agroforestry systems occurs both in aboveground and belowground components. However, the potential of any agroforestry system to sequester C depends on several factors such as land use type, site characteristics, tree species, stand age, and the management practices. Therefore, in order to evaluate the C sequestration potential of these woodlot systems in Tanzania, estimation of their above-and belowground C stocks is very important. In this chapter, we estimated the biomass C stocks in planted woodlots and ngitili systems to assess the C sequestration potential of the woodlots relative to the ngitili systems.

### 3.2. Abstract

Woodlots hold high promise to reduce forest degradation and offset carbon dioxide ($CO_2$) emissions mainly through on-farm wood production for fuelwood and charcoal supply and other related uses. Besides providing grazing areas and fuelwood, substantial amounts of C are stored in woodlots and ngitili land use systems. Despite the considerable attention that woodlots and ngitili systems in the Shinyanga region have received on their carbon sequestration potential (CSP), biomass carbon pools are lacking for the majority of these woodlot species and ngitili systems. The objective of this study was to estimate the biomass carbon stocks in planted woodlots of *Gmelina arborea, Melia azedarach*, *Albizia lebbeck,* and *Leucaena leucocephala* as well as in ngitili systems in the Kahama and Shinyanga rural districts in the Shinyanga region. Aboveground biomass carbon in the woodlots from the Kahama district ranged from 11.76 Mg C ha$^{-1}$ for *Melia azedarach* to 24.40 Mg C ha$^{-1}$ for *Albizia lebbeck*. However, based on the age of woodlots and the rate of CSP estimates, *Gmelina arborea* had the highest rate of aboveground C sequestration (3.59 Mg C ha$^{-1}$ year$^{-1}$) compared to the other woodlot species in this study. The woodlots had similar levels of biomass C compared to the Kahama district reserved ngitili (22.46 Mg C ha$^{-1}$). Degradation of ngitili in the Kahama district reduced the aboveground biomass C stocks by 15.11 Mg C ha$^{-1}$. Between the two districts, biomass C was higher in the Kahama district, which is relatively wetter than the Shinyanga rural district. The ability of the planted woodlots to store C similar to levels in the ngitili system indicates that the adoption of woodlots as a land use practice, in addition to addressing fuelwood deficit would also help to combating global warming through biomass C sequestration.

### 3.3. Introduction

The use of afforestation and reforestation to offset $CO_2$ emissions has resulted in the recognition of agroforestry as a land use system to capture and store atmospheric $CO_2$ in plant biomass (Nair, 2011). Agroforestry, which is a land use system that incorporates trees or other woody perennials in farmlands, pasture and/or livestock, holds great promise in atmospheric C sequestration (Albrecht and Kandji, 2003; Nair et al., 2010). Aboveground C estimates for agroforestry systems have been estimated to range from 0.29 to 15.21 Mg $ha^{-1}$ $yr^{-1}$ (Nair et al., 2010). The C sequestration potential of an agroforestry system depends on the environmental conditions, the species involved in the system and the system management (Albrecht and Kandji, 2003).

Rotational woodlot is an agroforestry technology comprising of sole stands of fast growing trees that are planted on farms and degraded lands for fuelwood, timber, and land restoration (Nyandzi et al., 2003). The practice of this agroforestry technology on farmlands consists of three inter-related management phases. The first phase is the establishment phase where trees are intercropped with crops for the first 2-3 years until canopy closure. Next is the tree-fallow phase where trees are allowed to build-up woody biomass and replenish soil nutrients. The third and final phase is a post-fallow period in which trees are harvested and crops grown with or without the coppiced tree stumps (Nyandzi et al., 2003; Kimaro et al., 2007a, 2007b). Comparatively, tree density in rotational woodlots is low (625-1,111 stems $ha^{-1}$) unlike other tree fallows established at higher plant densities (10,000 stems $ha^{-1}$) (Kimaro et al., 2007b).

Small-scale village woodlots and ngitili systems are common land use systems in the Shinyanga region of Tanzania for fodder and other tree-related benefits. 'Ngitili' is a traditional method of natural regeneration that involves management of natural vegetation and woodlands for fodder (Nyandzi et al., 2003; Zahabu and Otsyina, 2010). These land use systems have been observed to hold high promise in their carbon sequestration potentials but little information is available on the carbon sequestration potential of these systems. Aboveground biomass (AGB) estimation is an essential aspect of biomass carbon studies (Mani and Parthasarathy, 2007). Generalized biomass equations have been developed for different forest types and tree species. The use of regression models for biomass estimation relies on tree growth parameters such as total height and tree diameter (Vashum and Jayakumar, 2012). Despite the considerable attention the woodlots and ngitili systems in the Shinyanga region have received on their carbon sequestration potentials, biomass carbon pools are lacking for the majority of these woodlot species and ngitili systems. Therefore, the objective of this study was to estimate the biomass carbon potentials of these land use systems in the Shinyanga region using developed equations from the literature and to evaluate the potential contribution of these land use systems in offsetting the global $CO_2$ emissions. The hypotheses to be tested are:

1. Planted woodlots of *Gmelina arborea, Melia azedarach, Albizia lebbeck,* and *Leucaena leucocephala* have similar biomass C sequestration potentials as the ngitili systems
2. Higher biomass C pools in the Kahama district than the Shinyanga rural district due to the relatively wetter condition in the Kahama district than Shinyanga rural district

## 3.4. Materials and methods

### 3.4.1. Study location

This study was conducted in the Shinyanga region (3˚45' S, 33˚00' E), Northwestern Tanzania (Fig 3.1). The Kahama and Shinyanga rural districts were considered for the selected land use systems. The Shinyanga region experiences a bimodal rainfall distribution characterized by two rainfall peaks per year - February to mid-May as long rains and mid-October to December as short rains with a mean annual rainfall of 700 mm and mean monthly temperatures between 27.6˚C and 30.2˚C (Nyadzi et al. 2003). Though both districts are found in the same region, the Kahama district is relatively wetter and located to the west of the Shinyanga rural district. The Kahama district is covered by natural forests dominated by the miombo woodland whereas the Shinyanga rural district is covered with plains of low sparse vegetation.

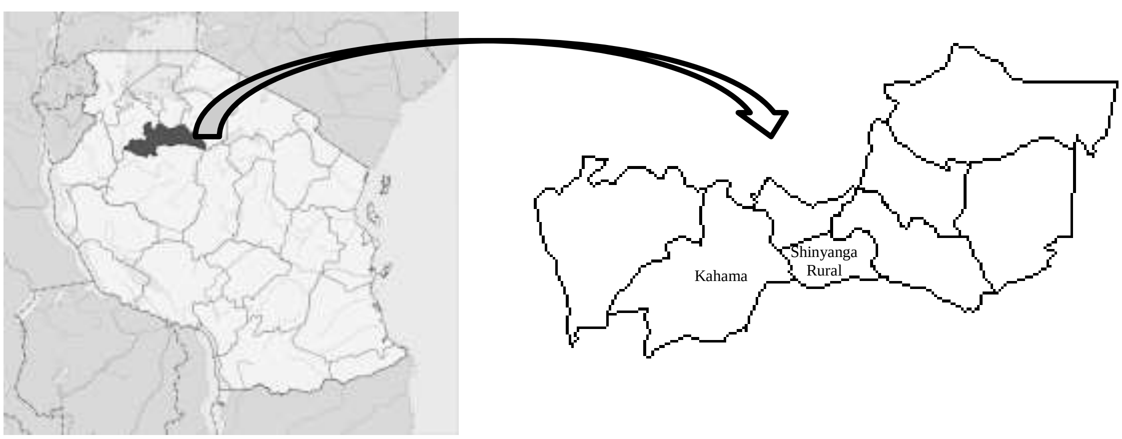


**Fig. 3.1. Map of Tanzania showing study sites in the Shinyanga region (Modified from www.commons.wikimedia.org).**

### 3.4.2. Selected land use systems

The land use systems that were considered in the Kahama district were: reserved ngitili (Fig. 3.2E), degraded ngitili (Fig. 3.2F), farmland and pure stand woodlots comprised of *Gmelina arborea* (Fig. 3.2A), *Melia azedarach* (Fig. 3.2B), *Albizia lebbeck* (Fig. 3.2C), or *Leucaena leucocephala* (Fig. 3.2D) species. Both the reserved and degraded ngitili in this district were made up of miombo vegetation woodlands. In the Shinyanga rural district, the land use systems consisted of a reserved ngitili of *Acacia drepanolobium* single-species stand (Fig. 3.3C), farmland, and pure woodlot stands of either *Leucaena leucocephala* (Fig. 3.3A) or *Albizia lebbeck* (Fig. 3.3B).

#### 3.4.2.1. Planted woodlots

Planting woodlots on scarce fallow or infertile patches of land is a common land management practice in the northern part of Tanzania for environmental rehabilitation and for other tree-related benefits (Luedeling et al., 2011). In the Shinyanga region, woodlots are often planted and managed on small-scales of less than 1 ha. They are planted on farms, community lands or degraded lands to produce wood for fuel, timber, and for land rehabilitation (Nyandzi et al., 2003). Tree species often planted include *Azadirachta indica*, *Albizia lebbeck*, *Leucaena leucocephala*, *Gmelina arborea, Melia azedarach, Eucalyptus species, Senna siamea, Senna spectabilis, Gliricidia sepium*, and *Tectona grandis*.

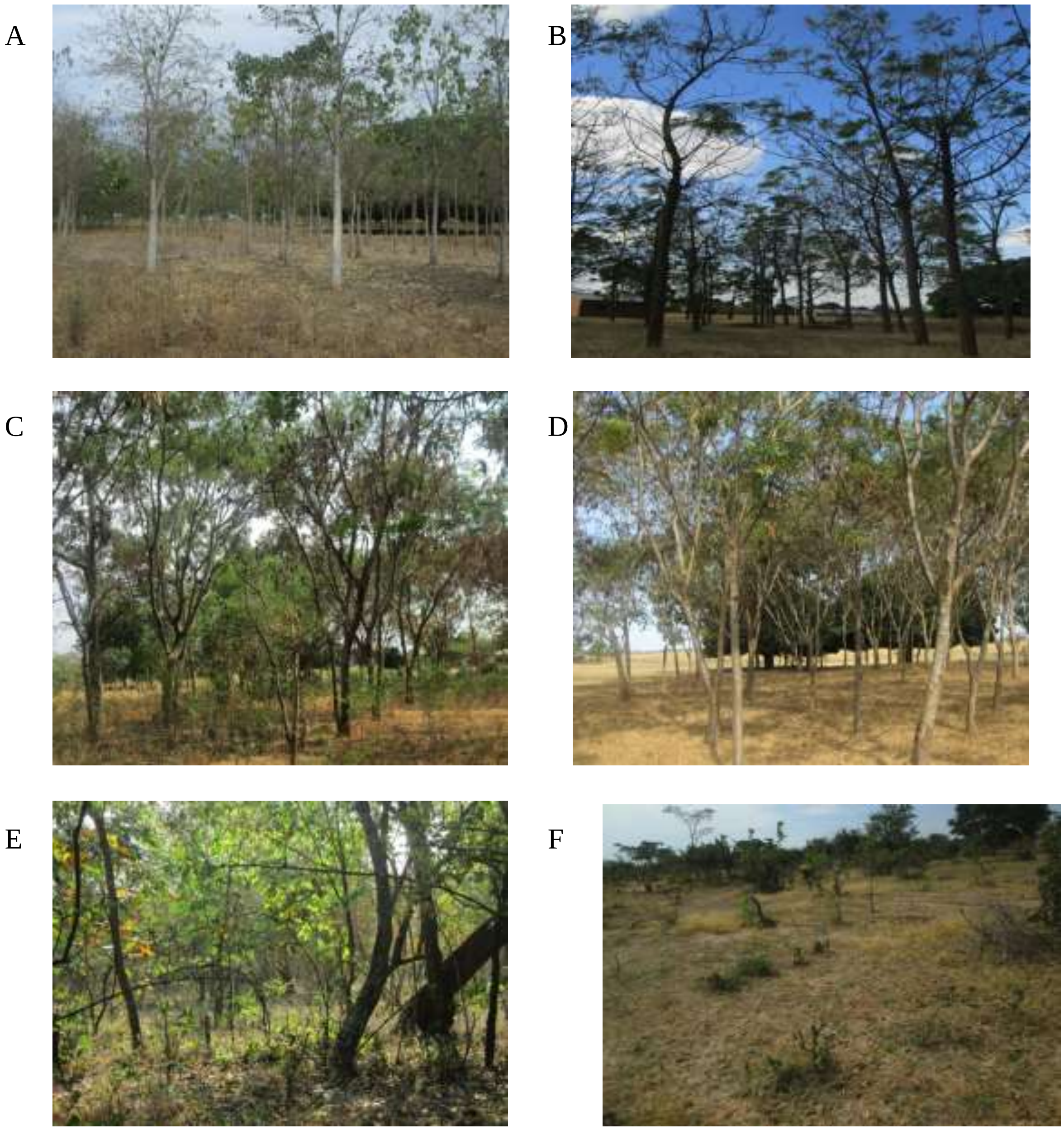


**Fig. 3.2. The selected land use systems of (A) *Gmelina arborea* (B) *Melia azedarach* (C) *Albizia lebbeck* (D) *Leucaena leucocephala* (E) Reserved ngitili and (F) Degraded ngitili in the Kahama district.**

A B C

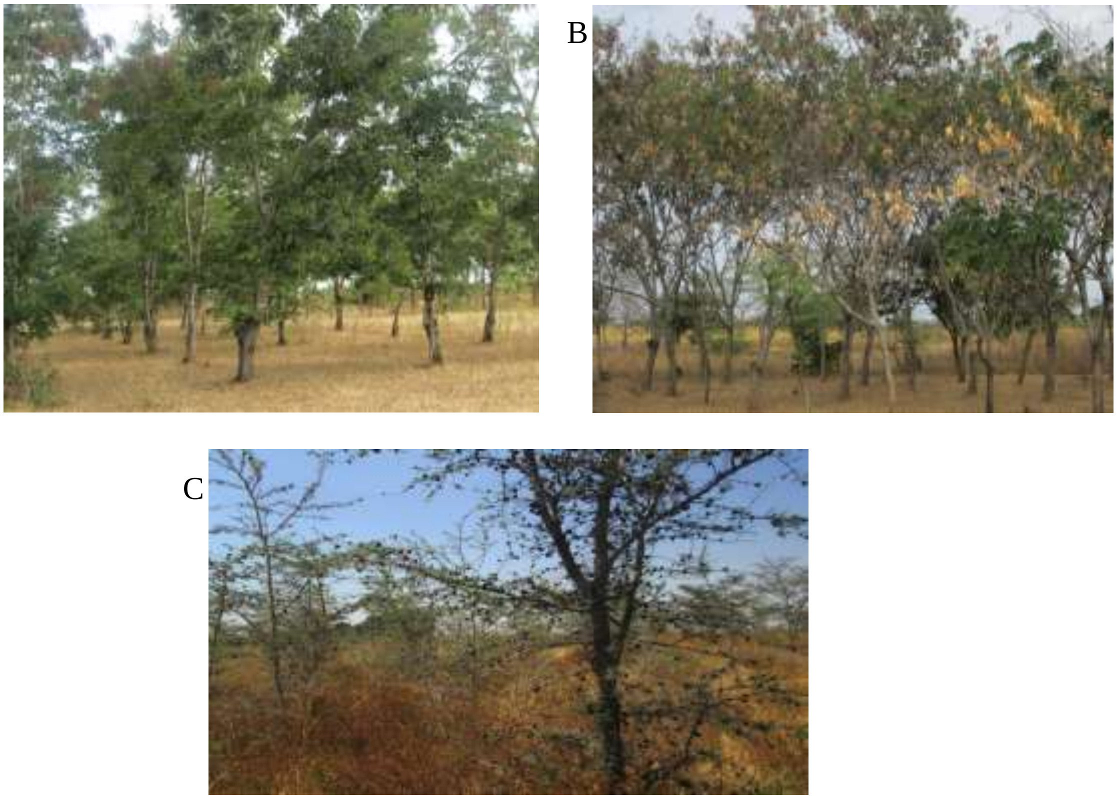

**Fig. 3.3. The selected land use systems of (A) Leucaena leucocephala (B) Albizia lebbeck and (C) reserved ngitili of *Acacia drepanolobium* species stand in the Shinyanga rural district.**

With respect to the woodlots considered in this study, apart from the *Gmelina arborea* woodlots from the Kahama district, which had a land area of 5 ha, all the other woodlot species from both districts had land areas of not more than 0.5 ha. Prior to the establishment of the *Albizia lebbeck* and *Leucaena leucocephala* woodlots in the Shinyanga rural district, the land was used for cotton production and then was left fallow for 3 years. In the Kahama district, the *Leucaena leucocephala* and *Melia azedarach* woodlots were established on highly eroded lands with the aim of providing vegetation cover to reduce erosion. This was different from the *Gmelina arborea* and *Albizia lebbeck*, which were established on farmlands and intercropped with cassava and maize. Apart from the *Albizia lebbeck* in the Shinyanga rural district, which had been coppiced in the past, none of the woodlot plantations from both districts had been coppiced since their establishment.

### 3.4.2.2. Ngitili systems

Ngitili is a traditional method of natural regeneration that involves management of natural vegetation and woodlands for fodder (Nyandzi et al., 2003; Zahabu and Otsyina, 2010). The reserved ngitili and degraded ngitili selected from the Kahama district are both community owned and managed. These two ngitilis are adjacent to each other and made of natural miombo woodland vegetation cover. Miombo woodlands are seasonally dry deciduous woodlands that are dominated by trees in the legume sub-family *Ceasalpinoideae* with the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* and a well-developed underlying layer of grass. This woodland covers about two thirds of the land area in Tanzania (Munishi et al., 2010). The degraded ngitili was an open-access woodland, which was allowed for animal grazing and wood harvest. Several dead tree stumps could be seen on the degraded ngitili site showing evidence of intense wood harvest. Unlike the ngitili systems in the Kahama district, which were rich in diverse species, the reserved ngitili in the Shinyanga rural district was a natural regeneration of *Acacia drepanolobium* single-species stand with undergrowth of grass. The reserved ngitili from the Shinyanga rural district was privately owned, which had been under reserve for more than 10 years.

### 3.4.3. Tree sampling and measurements

Two concentric plots of 20 m radius each were randomly located in each land use type for tree measurements in the woodlot and ngitili systems. Tree measurements for diameter at breast height (1.3 m from ground level) (DBH) and basal diameter (0.3 m from ground level) (D) were done using calipers and the Suunto PM-5/360PC clinometer was used for height (Ht) measurements. Within each plot, trees were sampled using the tree sampling protocol as proposed by Zahabu and Otsyina (2010). Diameter at breast height was measured for all trees greater than 1, 5, 10, and 20 cm diameter for trees within a radius of 2, 5, 10 and 15 m, respectively (Fig. 3.4).

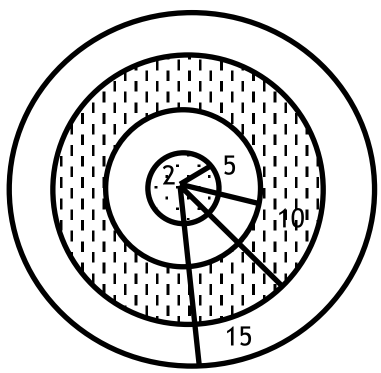


**Fig. 3.4. Layout of the plot using the specified radii: 2, 5, 10 and 15 m**
**Source: Zahabu and Otsyina (2010)**

### 3.4.4. Estimation of biomass carbon stocks

Aboveground biomass (AGB) for the woodlot species was calculated using species-specific allometric relationships developed from other tropical countries whereas those of the ngitilis were calculated from allometric relationships developed in the miombo woodlands in Tanzania (Table 3.1). Since the reserved ngitili in the Shinyanga rural district was a sole stand of *Acacia drepanolobium*, the allometric relationship for the biomass estimation in this ngitili was developed from *A. drepanolobium* biomass equation from the neighboring country, Kenya. Estimation of belowground biomass (BGB) for tree roots is uncommon in the literature. The BGB was calculated in the literature by multiplying AGB with a root to shoot ratio of 0.26 based on the work of Kaonga and Bayliss-Smith (2009). Biomass carbon was estimated as 50 % of wood biomass.

**Table 3.1. Allometric equations used in the biomass estimation**

| **Land use systems** | **Equation†** | $\mathbf{R^2}$ | **Source** |
|---|---|---|---|
| Kahama ngitilis | $Y = exp\,[-2.2453 + 2.4735 ln(dbh)]$ | 0.950 | Mugasha et al. (2012) |
| Shinyanga rural ngitili (*Acacia drepanolobium*) | $Y = 3.7704D + 1.1682$ | 0.964 | Okello et al. (2001) |
| *Melia azedarach* | $Y = -2.588 + 2.040D$ | 0.890 | Toky et al. (2011) |
| *Albizia lebbeck* | $lnY = 0.594 + 0.867 ln(dbh^2 Ht)$ | 0.980 | Singh et al. (2004) |
| *Leucaena leucocephala* | $Y = 0.206 dbh^{2.305}$ | 0.973 | Banaticla et al. (2007) |
| *Gmelina arborea* | $Y = 0.153 dbh^{2.217}$ | 0.994 | Banaticla et al. (2007) |

† Y, aboveground biomass (kg); D, basal diameter (cm); dbh, diameter at breast height (cm); Ht, height (m).

### 3.4.5. Statistical analysis

Data was analyzed using SAS 9.2 for Windows (SAS, 2008) using one-way analysis of variance (ANOVA) by the PROC GLM procedure at 5 % level of significance. Treatment means were separated using the Tukey’s Honestly Significant Difference (HSD). The SAS macro pdmix800 was used to perform pairwise comparisons at 5 % level of significance (Saxton, 1998).

### 3.5. Results

#### 3.5.1. Tree stand characteristics of study sites

The mean stand density from the study sites for the Kahama and Shinyanga rural districts was 455 stems ha$^{-1}$, ranging from 147 stems ha$^{-1}$ for the degraded ngitili to 780 stems ha$^{-1}$ for the *Gmelina arborea* both in the Kahama district (Table 3.2). On average, the Kahama district had a higher density of 523 stems ha$^{-1}$ compared to 317 stems ha$^{-1}$ for the Shinyanga rural district. The basal area (BA) of the Kahama district site (mean 9.64 m$^2$ ha$^{-1}$) ranged from 2.31 m$^2$ ha$^{-1}$ (in degraded ngitili) to 16.59 m$^2$ ha$^{-1}$ (in *Melia azedarach*); whereas in the Shinyanga rural district, the BA (mean 4.26 m$^2$ ha$^{-1}$) ranged from 0.44 m$^2$ ha$^{-1}$ (in reserved ngitili) to 7.35 m$^2$ ha$^{-1}$ (in *Leucaena leucocephala*) (Table 3.2). For the Kahama district, the basal diameter (D) and diameter at breast height (DBH) were higher in the planted woodlots than the reserved and degraded ngitilis. The mean D for the various land use systems in the Kahama district ranked from highest to lowest were *Albizia lebbeck* (21.9 $\pm$ 6.33 cm) $>$ *Melia azedarach* (21.4 $\pm$ 5.25 cm) $>$ *Gmelina arborea* (17.3 $\pm$ 3.55 cm) $>$ *Leucaena leucocephala* (15.9 $\pm$ 5.21 cm) $>$ degraded ngitili (13.6 $\pm$ 11.57 cm) $>$ reserved ngitili (11.5 $\pm$ 10.05 cm). Mean DBH, however, was ranked as *Melia azedarach* (18.7 $\pm$ 4.37 cm) $>$ *Albizia lebbeck* (17.3 $\pm$ 5.32 cm) $>$ *Gmelina arborea* (13.9 $\pm$ 2.91 cm) $>$ *Leucaena leucocephala* (12.3 $\pm$ 4.16 cm) $>$ degraded ngitili (10.1$\pm$ 9.98 cm) $>$ reserved ngitili (9.2 $\pm$ 8.15 cm). In the Shinyanga rural district, the mean D was ranked as *Leucaena leucocephala* (18.6 $\pm$ 5.33 cm) $>$ *Albizia lebbeck* (14.0 $\pm$ 3.84 cm) $>$ reserved ngitili (6.7 $\pm$ 2.18 cm). The mean DBH was also ranked in the same order as the mean D. *Leucaena leucocephala* (15.8 $\pm$ 5.58 cm) $>$ *Albizia lebbeck* (11.2 $\pm$ 4.20 cm) $>$ reserved ngitili (5.4 $\pm$ 1.97 cm) (Table

3.2). About 80 % of the trees in the ngitili systems from both districts had DBH of 10 cm and below compared to 18 % in the planted woodlots (Fig. 3.5).

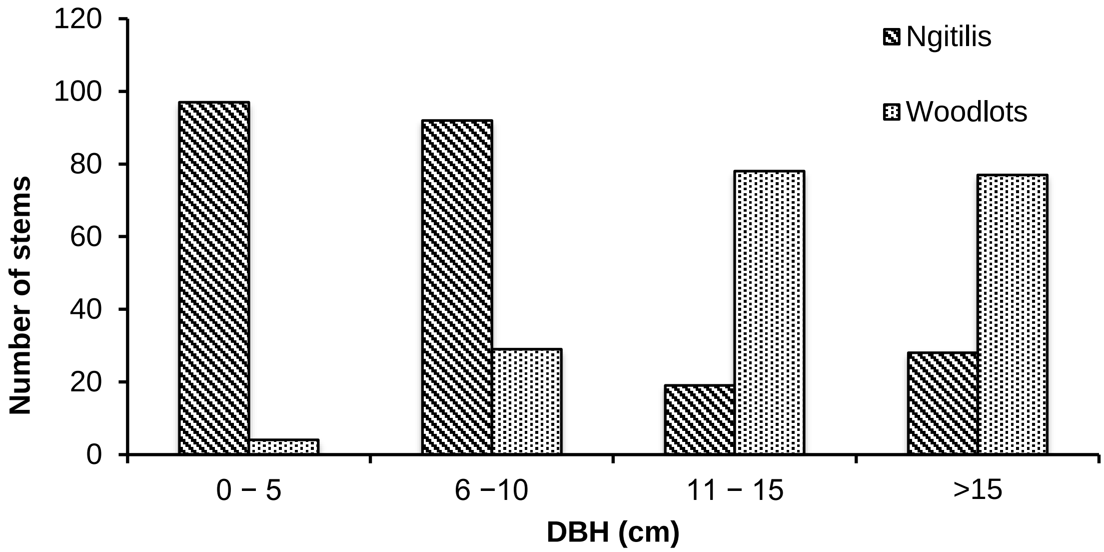


**Fig. 3.5. Frequency distribution of diameter at breast height (DBH) for the ngitilis and planted woodlots in the Kahama and Shinyanga rural districts, Tanzania**

**Table 3.2. Tree stand characteristics for the different land use systems in the Kahama and Shinyanga rural districts, Tanzania.**

| Site | Age | Stem density | Basal diameter (cm) | | | Diameter at breast height (cm) | | | Tree height (m) | | | Basal area |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | yrs | n $ha^{-1}$ | mean | min | max | mean | min | max | mean | min | max | ($m^2$ $ha^{-1}$) |
| Kahama district | | | | | | | | | | | | |
| Reserved ngitili | 20 | 621 | 11.5 | 2.0 | 61.0 | 9.2 | 1.0 | 60.0 | 6.7 | 1.8 | 21.6 | 7.30 |
| Degraded ngitili | 20 | 147 | 13.6 | 2.5 | 46.5 | 10.1 | 1.8 | 43.5 | 4.3 | 1.3 | 9.6 | 2.31 |
| *Melia azedarach* | 17 | 573 | 21.4 | 10.5 | 40.0 | 18.7 | 8.5 | 33.7 | 10.1 | 3.6 | 16.0 | 16.59 |
| *Gmelina arborea* | 6 | 780 | 17.3 | 6.4 | 23.8 | 13.9 | 4.8 | 18.8 | 6.6 | 4.1 | 7.6 | 12.33 |
| *Albizia lebbeck* | 17 | 477 | 21.9 | 10.6 | 33.5 | 17.3 | 6.0 | 26.4 | 8.8 | 4.1 | 12.6 | 12.21 |
| *Leucaena leucocephala* | 17 | 541 | 15.9 | 6.6 | 25.0 | 12.3 | 5.0 | 22.0 | 8.8 | 2.8 | 10.6 | 7.10 |
| Shinyanga rural district | | | | | | | | | | | | |
| Reserved ngitili | 10 | 171 | 6.7 | 2.5 | 11.0 | 5.4 | 1.0 | 9.1 | 3.9 | 2.1 | 5.2 | 0.44 |
| *Albizia lebbeck* | 18 | 447 | 14.0 | 8.7 | 19.2 | 11.2 | 6.0 | 18.0 | 5.7 | 3.3 | 7.1 | 4.99 |
| *Leucaena leucocephala* | 18 | 334 | 18.6 | 5.5 | 30.0 | 15.8 | 4.1 | 26.0 | 7.8 | 7.0 | 8.1 | 7.35 |

### 3.5.2. Biomass and biomass carbon stocks

#### *3.5.2.1. Aboveground biomass yield*

Aboveground biomass (AGB) in the land use systems from the Kahama district ranged from 14.70 Mg $ha^{-1}$ in the degraded ngitili to 48.80 Mg $ha^{-1}$ in the *Albizia lebbeck* (Fig. 3.6A) whereas those in the Shinyanga rural district ranged from 4.50 Mg $ha^{-1}$ in the reserved ngitili to 47.14 Mg $ha^{-1}$ in the *Leucaena leucocephala* (Fig. 3.6B). On average, AGB was ranked as *Albizia lebbeck* > reserved ngitili > *Gmelina arborea* > *Leucaena leucocephala* > *Melia azedarach* > degraded ngitili (Fig. 3.6A). Despite *Melia azedarach* having the lowest biomass production among the woodlot species in the Kahama district, AGB for the *Melia azedarach* was 60 % more than the degraded ngitili (Fig. 3.6A). Between the two ngitilis in the Kahama district, the reserved ngitili had 206 % more AGB than the degraded ngitili.

In the Shinyanga rural district, AGB was highest in the *Leucaena leucocephala* and lowest in the reserved ngitili, with the *Albizia lebbeck* in between them (Fig. 3.6B). Aboveground biomass in the *Leucaena leucocephala* was more than three times higher than the *Albizia lebbeck* and ten times higher than in the reserved ngitili (Fig. 3.6B). Between the two ngitili systems in the Kahama district, the degraded ngitili had lower biomass (14.70 Mg $ha^{-1}$) compared to 44.91 Mg $ha^{-1}$ in the reserved ngitili (Fig. 3.5A). Between the two districts, *Albizia lebbeck* in the Kahama district had 220 % more AGB than in the Shinyanga rural district; whereas the AGB in the *Leucaena leucocephala* was 12 % higher in the Shinyanga rural district than the Kahama district (Fig. 3.7).

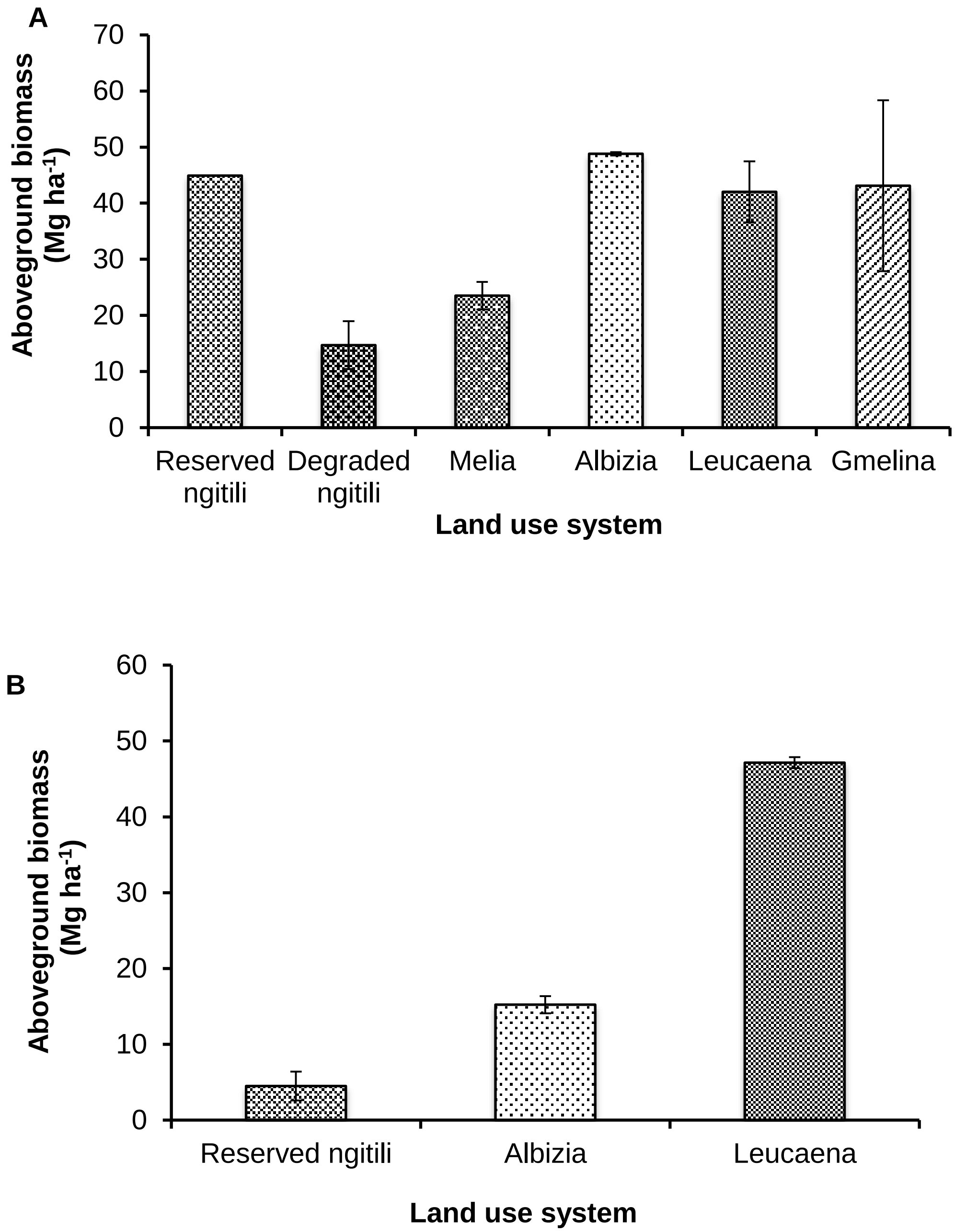


**Fig. 3.6. Aboveground biomass in different land use systems in the Kahama (A) and Shinyanga rural (B) districts, Tanzania. Error bars show standard error of means (n=2).**

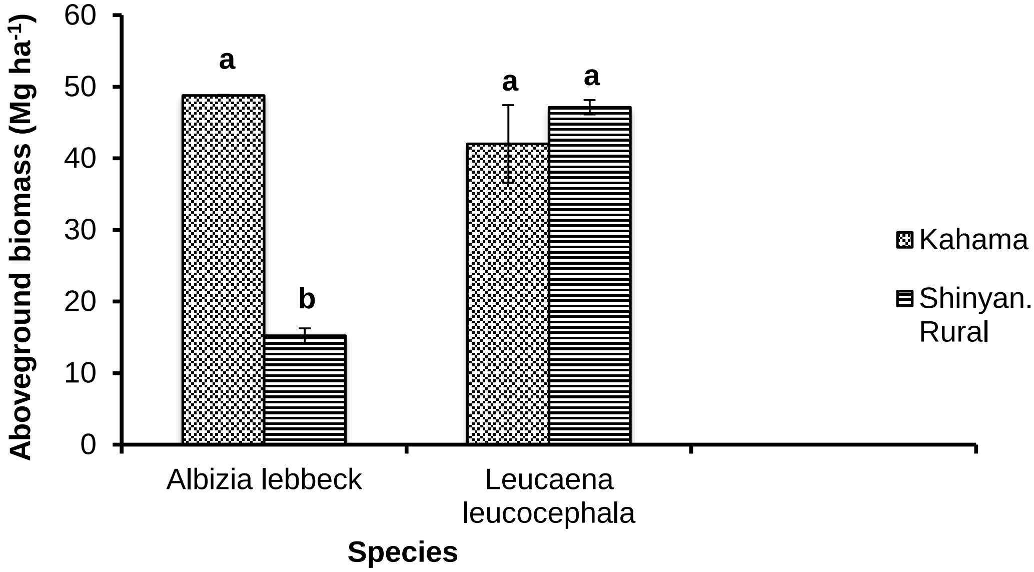


**Fig. 3.7. Comparison of aboveground biomass in *Albizia lebbeck* and *Leucaena leucocephala* in the Kahama and Shinyanga rural districts, Tanzania. Error bars show standard error of means (n=2). Error bars with same letters show means are not significantly different ($p$ > 0.05) according to the Tukey's Honestly Significant Difference (HSD).**

### *3.5.2.2. Aboveground and total biomass carbon stocks*

Considering that the aboveground biomass C (AGBC) stocks were estimated as 50 % of the AGB, differences in the AGBC followed the same trend as the AGB. The total biomass C (TBC) stocks were estimated as a sum of the AGBC and root C (RC) stocks (Table 3.3). The AGBC and TBC were ranked in the same order as the AGB in both districts. In the Kahama district, the AGBC and TBC were ranked as *Albizia lebbeck* > reserved ngitili > *Gmelina arborea* > *Leucaena leucocephala* > *Melia azedarach* > degraded ngitili and in the Shinyanga rural district, AGBC and TBC were ranked as *Leucaena leucocephala* > *Albizia lebbeck* > reserved ngitili (Table 3.3).

**Table 3.3. Carbon stocks in tree biomass for the different land use systems in the Kahama and Shinyanga rural districts in the Shinyanga region, Northwestern Tanzania.**

| Land use system | Aboveground carbon | Root carbon | Total biomass carbon |
|---|---|---|---|
| | ---------------------------- ($Mg\ ha^{-1}$) | ------------------------- | |
| | ------------------------ Kahama district | --------------------- | |
| Reserved ngitili | 22.46 (0.003)† | 5.84 (0.001) | 28.30 (0.004) |
| Degraded ngitili | 7.35 (1.503) | 1.91 (0.391) | 9.26 (1.894) |
| *Melia azedarach* | 11.76 (0.877) | 3.06 (0.228) | 14.82 (1.105) |
| *Albizia lebbeck* | 24.40 (0.110) | 6.34 (0.029) | 30.74 (0.139) |
| *Leucaena leucocephala* | 21.01 (1.920) | 5.46 (0.499) | 26.47 (2.419) |
| *Gmelina arborea* | 21.56 (5.381) | 5.61 (1.399) | 27.17 (6.780) |
| | ------------------ Shinyanga rural district | ---------------- | |
| Reserved ngitili (*A. drepanolobium*) | 2.25 (0.672) | 0.59 (0.175) | 2.84 (0.847) |
| *Albizia lebbeck* | 7.62 (0.403) | 1.98 (0.105) | 9.60 (0.508) |
| *Leucaena leucocephala* | 23.57 (0.262) | 6.13 (0.068) | 29.70 (0.330) |

† SEM, standard error of means.

## 3.6. Discussion

### 3.6.1. Tree stand characteristics of study sites

The number of stems per hectare varied with land use systems within and between the Kahama and Shinyanga rural districts. The stem diameter (DBH) distribution of the ngitili systems from both districts followed the reversed J-shaped trend with high number of trees below 10 cm DBH (Fig. 3.5) as observed by Monela et al. (2005). Between the reserved and degraded ngitilis in the Kahama district, about 74 % of trees in the reserved ngitili had DBH below 10 cm compared to 62 % in the degraded ngitili. The dominance of young trees with smaller diameters in the reserved ngitili is indicative of regeneration occurring from the closure of the woodland, which had previously been under degradation. This is different from the degraded ngitili where trees are selectively and intensively harvested as well as disturbances from grazing animals which is a common practice in the Shinyanga region (Monela et al., 2005). The woodlots on the other hand followed the J-shape diameter distribution pattern with a higher number of the trees above 10 cm DBH indicating good growth rates (Shirima et al., 2011).

The number of stems for the reserved ngitili in the Kahama district (621 stems $ha^{-1}$) was lower than 6553 stems $ha^{-1}$ reported by Monela et al. (2005) for ngitilis in the district. Since the regenerations in the reserved ngitilis occurring from the closure of previously degraded ngitilis are through coppice regrowth and root suckers rather than through seeds (Monela et al., 2005), the age and period of regrowth of an ngitili is likely to influence the number and size of stems found in that ngitili. Shirima et al. (2011) indicated that the period and level of disturbance as well as the site characteristics greatly influence the tree stand characteristics of woodlands. Therefore, the lower number of stems in this study compared to the study by Monela et al. (2005) could be due to differences in the age, regrowth period and site characteristics of the reserved ngitili in our study site in the Kahama district compared to the study sites by Monela et al. (2005). The higher BA for the reserved ngitili in the Kahama district (7.30 $m^2$ $ha^{-1}$) compared to the 5.76 $m^2$ $ha^{-1}$ reported in the same district by Monela et al. (2005) could also be attributed to differences in site characteristics and disturbance regimes. Both the number of stems (147 stems $ha^{-1}$) and the BA (2.31 $m^2$ $ha^{-1}$) of the degraded ngitili in the Kahama district were less than those reported for this district by Monela et al. (2005). Owing to wood harvest and disturbance by grazing animals, which were the observed major causes of degradation in the degraded ngitili, stocking density was reduced by more than 4.5 times in the degraded ngitili compared to the reserved ngitili in the Kahama district.

The reserved ngitili in the Shinyanga rural district, which was an *Acacia drepanolobium* bushland, had lower tree density (171 stems $ha^{-1}$) and BA (0.44 $m^2$ $ha^{-1}$)

than the reserved ngitili in the Kahama district. This is consistent with the assertion by Monela et al. (2005) that miombo woodlands (in this study; the reserved ngitili in the Kahama district) have higher stocking densities and BA than bushlands (in this study; reserved ngitili in the Shinyanga rural district). Both the tree density and BA for the reserved ngitili in the Shinyanga rural district were less than those reported for ngitilis in this district by Monela et al. (2005). The lower tree density and BA in the reserved ngitili from the Shinyanga rural district compared to the study by Monela et al. (2005) was expected because the site considered by Monela et al. was a miombo woodland compared to the *Acacia* bushland in our study.

With regards to the planted woodlot species from both districts, apart from the *Gmelina arborea*, which had a stocking density of 780 stems $ha^{-1}$ and within the required range of 652-1,111 stems $ha^{-1}$ for planted woodlots (Kimaro et al., 2007b), stocking densities for the other woodlot species were lower. The *Melia azedarach* exhibited faster growth (as measured in D, DBH, and Ht) compared to the other woodlot species; however, a consideration of age showed that the *Gmelina arborea* had faster growth rate as this species was 6-years old compared to 17-years for the Kahama woodlots and 18-years for the Shinyanga rural district woodlots. The variations observed in the growth rates among the different tree species could be explained by the genetic variation and differences in requirements of climatic, site and management practices (Chauhan et al., 2009). Generally, the Kahama district had higher stocking tree density (mean: 523 stems $ha^{-1}$) compared to the Shinyanga rural district (mean: 317 stems $ha^{-1}$). The higher tree stocking densities observed in the Kahama district than the Shinyanga rural district could be attributed to differences in site characteristics such as climate and soil conditions. The

Kahama district is relatively wetter than the Shinyanga rural district (HASHI, 2002). The wetter conditions in the Kahama district than the Shinyanga rural district is likely to provide better growth conditions in the Kahama district than the Shinyanga rural district.

### 3.6.2. Biomass yield and biomass carbon stocks

The biomass C estimated in this study represent the biomass C sequestration potentials of the woodlots and ngitili systems in the Kahama and Shinyanga rural districts. The carbon sequestration potential (CSP) from the Kahama district planted woodlots, which ranged from 11.76 Mg C $ha^{-1}$ to 24.40 Mg C $ha^{-1}$ showed higher CSP in *Albizia lebbeck* than the other woodlot species. These estimates are within the reported range of 11.5-25.5 Mg C $ha^{-1}$ for rotational woodlots in Tanzania (Kimaro et al., 2007b). However, considering that the *Gmelina arborea* was younger in terms of age than the other species from the Kahama district, the *Gmelina arborea* had the highest CSP rates (3.59 Mg C $ha^{-1}$ $year^{-1}$) compared to the *Albizia lebbeck* (1.44 Mg C $ha^{-1}$ $year^{-1}$), *Leucaena leucocephala* (1.24 Mg C $ha^{-1}$ $year^{-1}$), and *Melia azedarach* (0.69 Mg C $ha^{-1}$ $year^{-1}$). The higher CSP rate in the *Gmelina arborea* than the other woodlot species in the Kahama district could be due to the higher tree density of the *Gmelina arborea*. Stocking density in the *Gmelina arborea* was 36 %, 44 %, and 64 % higher than the *Melia azedarach*, *Leucaena leucocephala*, and *Albizia lebbeck* from the Kahama district, respectively. Higher stocking levels of trees have been indicated to enhance vegetation C pools (Nair et al., 2010). Also, differences in climatic requirements, site characteristics, management practices, and genetic variations have been explained to influence biomass production and for that matter biomass CSP (Chauhan et al., 2009). The higher sequestration rate exhibited by the *Gmelina arborea* compared to the *Albizia lebbeck*, *Leucaena leucocephala*, and *Melia azedarach,* which were all under the same management systems and from the same district and climate could mean that the climatic requirements and soil characteristics in the Kahama district were more favourable to the *Gmelina arborea* for biomass production resulting in a higher rate of C sequestration. Chauhan et al. (2009) observed about 64 % more AGB in *Gmelina arborea* than *Melia azedarach,* which shows the higher potential of *Gmelina arborea* for biomass production compared to other agroforestry species.

Comparing the biomass and C stocks in the *Albizia lebbeck* and *Leucaena leucocephala* from the Kahama district to those in the Shinyanga rural district, the *Albizia lebbeck* in the Kahama district had more than three times the C stocks in the Shinyanga rural district *Albizia lebbeck* whereas the *Leucaena leucocephala* from the two districts showed very little difference in C stocks. The higher biomass and C stocks in the *Albizia lebbeck* from the Kahama district than the Shinyanga rural district may be owing to differences in site growth conditions and tree density. Shirima et al. (2011) has shown that biomass and C in tropical savannah ecosystems are influenced by rainfall, temperature, and soil characteristics. Tree density in the *Albizia lebbeck* was 7 % higher in the Kahama district than the Shinyanga rural district. The wetter conditions in the Kahama district will likely provide better growth conditions than the Shinyanga rural district leading to higher biomass production in the Kahama district than the Shinyanga rural district. Between the *Leucaena leucocephala* and the *Albizia lebbeck* in the Shinyanga rural district, the *Leucaena leucocephala* had a higher biomass and C stock than the *Albizia lebbeck* due to differences in species. The rate of biomass production has been argued to strongly depend on the species, nutrient supply, and the efficiency of soil nutrient use (Singh et al., 2004; Kimaro et al., 2007a). The differences in the ability of different species to efficiently use limited nutrients for biomass production could be the result of the variations in the biomass and C stocks between the *Leucaena leucocephala* and the *Albizia lebbeck* in the Shinyanga rural district. The C sequestration rate for the planted woodlot species reported in this study fall within the range of values (1.50-6.55 Mg C $ha^{-1}$ $year^{-1}$) reported for tropical agroforestry systems (Nair et al., 2009).

On the part of the ngitili systems, the reserved ngitili in the Kahama district had more biomass and C stocks than the reserved ngitili in the Shinyanga rural district. Differences in growth conditions and species composition from the two districts could be attributed to the differences in their biomass and C stocks. The reserved ngitili from the Kahama district, which was a miombo woodland had higher tree density and species composition dominated by *Brachystegia spiciformis, Combretum zeyheri, Combretum molle,* and *Brachystegia bussei* compared to the reserved ngitili from the Shinyanga rural district, which had lower tree density and a bushland single-species of *Acacia drepanolobium*. The canopy was more closed in the Kahama district reserved ngitili than the Shinyanga rural district reserved ngitili because of the wetter conditions in the Kahama district than the Shinyanga rural district. Shirima et al. (2011) observed differences in biomass and C stocks from two miombo woodlands in Tanzania, which they attributed to differences in canopy cover, rainfall and temperature differences between the sites. Biomass C accumulation has also been observed to increase with the growth stage of trees, with older trees (> 10 cm DBH) containing more C stocks than younger trees (Madoffe et al., 2012). Therefore, the higher C stocks in the reserved ngitili in the Kahama district than the Shinyanga rural district could be due to the age differences of the ngitilis in the two districts. The Kahama reserved ngitili had been under reserve for about 20 years compared to the 10 years in the Shinyanga rural district reserved ngitili. The age difference could also be evidenced in their measured DBH where 26 % of trees in the Kahama district reserved ngitili had DBH of 10 cm and above compared to the Shinyanga rural district where none of the trees had DBH of up to 10 cm. Between the reserved and degraded ngitili from the Kahama district, degradation of the ngitili (miombo woodland) reduced the aboveground biomass C stocks by 15.11 Mg C $ha^{-1}$. Williams et al. (2008) observed a 19.0 Mg C $ha^{-1}$ reduction in wood C stocks after the clearance of miombo woodland in Mozambique to agricultural land.

### 3.6.3. Comparison of estimates with other related studies

The estimated CSP of the woodlot species and ngitili systems in this study compare very well with studies from other regions. Although the reserved ngitili in the Kahama district was a regeneration from previously degraded miombo woodland, its AGBC stock of 22.46 Mg C $ha^{-1}$ was similar to the 22.5 Mg C $ha^{-1}$ reported by Zahabu et al. (2008) and also within the range reported in other miombo woodlands by Shirima et al. (2011) and Madoffe et al. (2012). The Kahama district reserved ngitili estimate is however, slightly higher than the estimated 19.12 Mg $ha^{-1}$ for miombo woodlands of the Southern Highlands of Tanzania (Munishi et al., 2010). Even though Munishi et al. (2010) indicated that their studied miombo woodland was in the early stages of regeneration after extensive exploitation, only trees $\geq$ 6 cm DBH were considered in their study. This was different from our study, which considered trees below 5 cm DBH. This and other factors such as differences in age, regrowth period of the woodlands and site characteristics could be attributed to the higher biomass and C stocks in our study. In the Shinyanga rural district reserved ngitili, the estimated 4.50 Mg $ha^{-1}$ for the AGB is within the 3.9-8.0 Mg $ha^{-1}$ range reported for different ngitili systems in the Shinyanga rural district (Zahabu et al., 2012). This estimate is higher than the 0.77-2.55 Mg $ha^{-1}$ range reported by Phabian (2012) for ngitilis in this district. The higher estimate in our study than the estimate by Phabian (2012) could be attributed to high level of disturbance from wood harvest and grazing cattle as indicated by Phabian (2012) in their ngitili systems. This was different from our studied ngitili site that had been under reserve for a decade with minimal or no disturbance.

Similarly, the biomass and C estimates in the woodlots compared well with same species studied in other regions. The AGBC (24.40 Mg C $ha^{-1}$) and the TBC (30.74 Mg C $ha^{-1}$) for the *Albizia lebbeck* in the Kahama district in this study were close to the 26.87 Mg C $ha^{-1}$ (AGBC) and 33.85 Mg C $ha^{-1}$ (TBC) reported by Chavan and Rasal (2012). However, these estimates are higher than the 7.62 Mg $ha^{-1}$ (AGBC) and 9.60 Mg $ha^{-1}$ (TBC) for the Shinyanga rural district *Albizia lebbeck* species. Also, the AGBC estimates for *Leucaena leucocephala* in this study (21.01 and 23.57 Mg C $ha^{-1}$ for Kahama district and Shinyanga rural district, respectively) were slightly lower than the 32 Mg C $ha^{-1}$ reported elsewhere (Albrecht and Kandji, 2003). Roy et al. (2006) estimated a total biomass of 21.1 Mg $ha^{-1}$ for *Melia azedarach.* This is lower than the 29.64 Mg $ha^{-1}$ estimated in this study and 38.4 Mg $ha^{-1}$ reported by Toky et al. (2011). The estimated 43.11 Mg $ha^{-1}$ AGB for *Gmelina arborea* in this study is in the reported range of 11-364 Mg $ha^{-1}$ from other studies (Banaticla et al., 2007) and close to the estimated 43.9 Mg

$ha^{-1}$ in a similar age *Gmelina arborea* plantation in India (Swamy et al., 2003). The differences in the estimated biomass and C stocks in our woodlot species compared to the same species in other studies point to differences in age, tree stand densities, management of practices and differences in site-specific characteristics.

### 3.7. Conclusion

The similar levels of biomass C in the reserved ngitili in the Kahama district to other miombo woodlands indicate the enormous potential these ngitili systems could have in biomass C sequestration when protected from degradation. As evidenced in the degraded ngitili from the same (Kahama) district, degradation of ngitili reduced aboveground biomass C stocks by 15.11 Mg C $ha^{-1}$. The higher biomass C values in the reserved ngitili from the Kahama district than the reserved ngitili in the Shinyanga rural district is an indication that site-specific characteristics, age of stand, and level of disturbance greatly influence the biomass C sequestration potentials of vegetation. Results for the aboveground CSP showed that woodlots in the drier Shinyanga region of Tanzania have high promise to sequester biomass C similar to the levels in the ngitili systems and other miombo woodlands. Based on the CSP estimates, *Gmelina arborea* had the highest rate of aboveground C sequestration (3.59 Mg C $ha^{-1}$ $year^{-1}$) compared to the other woodlot species in this study. With adjacent communities to forestlands more likely to create high degradation pressure on these forestlands by continuously depending on them for fuelwood, building poles, timber, and other related purposes, the adoption of woodlots as a land use practice will address these issues with the added benefit of combating global warming. Carbon from these woodlots can also be a source of revenue from C trading and under proper benefit sharing mechanisms, can contribute to poverty reduction among local communities.

# 4. SOIL CARBON STOCKS IN PLANTED WOODLOTS AND NGITILI SYSTEMS IN SHINYANGA, TANZANIA

## 4.1. Preface

Chapter 4 quantifies SOC storage in whole soil and different soil fractions under woodlots, ngitili and farmland systems. The soil C sequestration potential of any system depends not only on the quantity and quality of the biomass input into the soil, but also by the properties of the soil such as aggregation. The influence of these land use systems on the SOM chemistry have also been studied in this chapter using the synchrotron-based technique. Results for SOC in the different aggregate classes and the influence of these land use systems on the SOM chemistry would help to identify which land use system contributes to more stable C in the soil.

## 4.2. Abstract

Long-term carbon (C) sequestration in soils under agroforestry systems has been observed as a viable option for possible climate change mitigation due. Soil organic carbon (SOC) stocks in woodlots in Tanzania have been less studied. This study evaluated SOC stock to 1 m depth in woodlots of *Albizia lebbeck, Leucaena leucocephala, Melia azedarach,* and *Gmelina arborea*; and in farmland and ngitili systems to understand the influence and efficacy of the woodlot technology on SOC storage. Soil samples were collected from selected sites in the Kahama and Shinyanga rural districts of Tanzania. The SOC stocks in whole soil for the land use systems from the two districts ranged from 43-67 Mg C $ha^{-1}$. Overall, SOC stocks did not differ with land use change indicating the ability of the planted woodlots on degraded lands to restore SOC levels similar to the natural woodlands. SOC was uniformly distributed in soil aggregates within the upper 0.4 m in the farmland from both districts and the ngitili systems in the Kahama district whereas the ngitili system in the Shinyanga rural district had 61 and 57 % more SOC in the macroaggregates (2000-250 μm) than the microaggregates (250-53 μm) and silt and clay fractions (<53 μm), respectively. The SOC in the woodlots were found to be associated more with the microaggregates, and silt and clay fractions than the macroaggregates, reflecting high stability of SOC in the woodlot systems. The XANES C K-edge spectra for the silt and clay sized aggregates in the upper 20 cm soil depth layer for the land use systems from the Kahama district showed the degradation of recalcitrant aromatic compounds in farmland and the ngitilis as evidenced by the presence of ketones. The continuous addition of litter in the woodlots appeared to have preserved the aromatic pools indicating the ability *Albizia lebbeck* and

*Leucaena leucocephala* have in storing more recalcitrant C in the silt and clay sized aggregates. This study demonstrates the significant contributions of woodlots to accumulate SOC and offset $CO_2$ emissions through the long-term stabilization of SOC in the soil aggregates. Thus, these agroforestry practices hold promise to meet household energy needs while contributing to climate change mitigation and adaption.

### 4.3. Introduction

Global interest to capture and store C in long-lived sinks stems from the increasing levels of atmospheric $CO_2$ and associated global warming. Long-term C sequestration in soils has been observed as a viable option for possible climate change mitigation due to the high potential soils have in C storage (CRS, 2007). The soil is estimated to contain 1500-2000 Pg C to a 1 m depth (Janzen, 2004), compared to 770 Pg C in the atmosphere and 610 Pg C in vegetation (Nair et al., 2009). The ability of the soil to act as a C sink depends on the environmental conditions and the land use practices (Marschner et al., 2008). Land use changes, which cause depletion of soil and biotic C pools results in SOC loss. These SOC losses can be resequestered by the adoption of restorative land practices such as agroforestry (Lal, 2003). As a result, agroforestry as a land use system has received wider recognition not only as a means of restoring degraded lands but also for C sequestration (Nair et al., 2009).

Rotational woodlots (an agroforestry technology), which were purposely established in Tanzania to supply on-farm fuelwood to reduce the high rate of deforestation, have also been recognized as potential C sequesters (Kimaro et al., 2007b). The potential of any agroforestry system in soil C sequestration is not only influenced by the quantity and quality of litter, but also by the properties of the soil such as soil structure and their aggregations (Nair et al., 2010). The association of SOC with different soil aggregates and the variable turnover rates of SOC in different aggregates means that not all C in the soil can be considered sequestered (Montagnini and Nair 2004). Soil organic carbon in macroaggregates, which represent recent C depositions in soils are more influenced by a change in land use system and soil management compared to the more stabilized C in microaggregates and silt and clay fractions (Saha et al., 2010).

The quality of litter also greatly influences the decomposition rates of SOM and as a result their stability in the soil. Unlike studies in soil C storage, interests in litter quality in soil fertility studies have focused on the ability of plant litter to readily release nutrients through mineralization. Residue quality indices such as C/N ratios and N have often been used as an index to assess the quality of plant litter. A study by Solomon et al. (2000) suggests that low quality litter indicated by high C/N ratios resulted in SOM accumulation and decreased rates of SOM degradation. This explains the importance of SOM chemistry in long-term soil C storage and hence their contribution in the global C cycle. It is therefore imperative to understand the influence of different land use systems on the chemistry of SOM in soil C studies. Knowledge about the influence of different land use systems on SOM chemistry will give an insight into how these land use types contribute to sequestering soil C and the stable form of the sequestered C.

Studies in the woodlot systems in Tanzania to evaluate their C sequestration potentials have not been exploited extensively. The few studies in these systems to evaluate their soil C sequestration potentials have focused on the upper soil layers ignoring the impact of these systems on soil aggregation as well; despite the importance soil aggregates have on SOC sequestration.

Therefore, the objective of this study was to evaluate the soil C sequestration potential of woodlots and other land use systems in the Shinyanga region and the impact these systems have on soil aggregation. The hypotheses to be tested are:

1. Planted woodlots of *Gmelina arborea, Melia azedarach*, *Albizia lebbeck*, and *Leucaena leucocephala* have similar SOC sequestration potentials as the ngitili

systems

2. Tree-based systems have higher SOC stocks in whole soil and soil aggregates than farmland due to organic matter inputs from the tree-based systems
3. SOM in farmland shows evidence of advanced degradation compared to the tree-based systems
4. Higher SOC stocks in the Kahama district than the Shinyanga rural district due to the relatively wetter condition in the Kahama district than Shinyanga rural district

## 4.4. Materials and methods

### 4.4.1. Soil sampling and preparation for analysis

This chapter focuses on the soil C stocks in planted woodlots, ngitili systems and farmlands from the Kahama and Shinyanga rural districts in Tanzania. Details of the study sites and the land use systems are described in Chapter 3, sections 3.4.1 and 3.4.2. Soil samples for this study were collected from woodlots of *Albizia lebbeck, Leucaena leucocephala, Melia azedarach,* and *Gmelina arborea*; farmland, and reserved and degraded ngitilis from the Kahama district. All these land use systems except for the *Melia azedarach, Gmelina arborea,* and degraded ngitili were also considered in the Shinyanga rural district. Three plots were randomly located in each of the land use systems from the two districts. A profile pit of 1 m × 1 m × 1 m size was dug in each of the plots and soils were sampled at depths 0-20, 20-40, 40-60, 60-80, and 80-100 cm. For each depth class in a profile pit, soils were collected from the four faces of the pit. The four sub-samples were composited to get one composite sample for each depth class per profile pit. Due to the underlying bedrock for the woodlot sites in the Shinyanga rural district, sampling depths were restricted to 40 cm and 80 cm for the *Albizia lebbeck* and *Leucaena leucocephala* plots, respectively. Soil sampling for bulk density (BD) measurement was done using a 5 cm dia.× 5 cm long steel core sampler. The steel sampler was inserted horizontally into the wall of the pits at the center of each depth class. Soils inside the sampler were collected and used for BD determination.

#### 4.4.2. Soil preparation and analysis

The sampled soils were air-dried at the National Forest Resources Management and Agroforestry Center (NAFRAC) lab in Shinyanga and brought to the University of Saskatchewan for analysis. Sub-samples taken from the air-dried samples after they had been passed through a 2 mm sieve were ground and analyzed (Table 4.1) for SOC by the dry combustion method using the LECO C632 carbon combustion analyzer (LECO® Corporation, St. Joseph, MI, USA) carbonator. Total inorganic N ($NO_3^-$ and $NH_4^+$) was analyzed colorimetrically using an autoanalyzer (Technicon Autoanalyzer, Technicon Industrial Systems, Tarrytown, NY, USA) after extraction with 2 *M* KCl solution (Maynard et al., 2008). Soil pH and electrical conductivity (EC) (1:2 soil:water, Hendershot et al., 2008) were determined using an Beckman 50 pH Meter ( Beckman Coulter, Fullerton, CA, USA) and an Accumet AP85 pH EC meter (Accumet, Hudson, MA, USA), respectively. Exchangeable $Ca^{2+}$, $K^+$ and $Mg^{2+}$ were analyzed after extraction with 1 *M* ammonium acetate solution using an atomic absorption spectrometer (AAS) (Varian SpectrAA 220, Burladingen, Germany) (Hendershot et al., 2008). Available phosphorus (P) was determined by an UVmini-1240 UV-Vis Spectrophotometer (Shimadzu Scientific Corporation, Japan, USA) after extraction with Bray 1 solution

(Bray and Kurtz, 1945). Particle size analysis was done by the modified pipette method (Indorante et al., 1990).

### 4.4.3. Fractionation of soil into aggregates

Sub-samples of the air-dried soils from 0-20 and 20-40 cm depths were physically fractionated into three aggregate size classes (250-2000 µm, 53-250 µm, and <53 µm) according to a wet-sieving procedure from Elliott (1986) and Six et al. (2002) that was adapted by Saha et al. (2010). The procedure involved passing 100 g of soil through two series of sieves to separate the soil into macroaggregates (250-2000 µm), microaggregates (53-250 µm), and silt-and clay-sized fraction (<53 µm). The separation was done after the samples were submerged in a 500 mL beaker of de-ionized water for about 5 minutes to release the air trapped inside the soil pores. The soil fractions were collected into aluminum pans and allowed to oven-dry at 65˚C. The different soil aggregates were ground with the ball-grinder and SOC was analyzed by dry combustion using the LECO C632 carbon combustion analyzer (LECO® Corporation, St. Joseph, MI, USA) carbonator.

### 4.4.4. Analysis by X-ray absorption near-edge structure (XANES) spectroscopy

XANES analysis was done for macro-sized and silt and clay-sized soil aggregates of reserved ngitili, degraded ngitili, farmland, *Leucaena leucocephala*, and *Albizia lebbeck* from the Kahama district; and reserved ngitili, farmland, *Leucaena leucocephala*, and *Albizia lebbeck* from the Shinyanga rural district for 0-20 and 20-40 cm depth classes. Carbon K-edge XANES spectra were collected using the Spherical Grating

Monochromator (SGM) beamline 11ID-1 at the Canadian Light Source (CLS, Saskatoon, Saskatchewan, Canada) in September 2013. Prior to the XANES spectra collection for each sample, subsamples were pulverised and slurried in water. Gold (Au)-coated plates were affixed to sample holders using double-sided carbon tape. The slurried samples were then fixed on the Au-coated plates and allowed to air-dry under room temperature before inserting them into the X-ray absorption vacuum chamber for the carbon spectra collection. The beamline at the time of the experiment delivered $10^{11}$ photons $s^{-1}$ at the C K-edge, with a resolving power ($E/\Delta E$) > 10,000 (Regier et al., 2007a, 2007b; Gillespie et al., 2014). The exit slit was set at 49.9 μm and partial fluorescence yield (PFY) data was collected using an Amptek silicon drift detector with region of interest set to C emission. The entire samples were scanned at a distance of 0.15 mm between individual measurement points. A minimum of 15 scans was done for each sample and scanning was done at energy range from 270 to 320 eV. For calibration at the C K-edge, a solid-state absorption spectrum for citric acid was measured. The beamline flux was measured with a Au photodiode to monitor fluctuations across the C K-edge that might have been caused by the presence of adventitious carbon on the beamline optics (Gillespie et al., 2014). The measured flux was used to normalize the carbon spectra that were collected and the XANES data was processed using custom macros in IGOR Pro (Wavemetrics, Lake Oswego, Oregon, USA).

### 4.4.5. Statistical analysis

Data was analyzed using SAS 9.2 for Windows (SAS, 2008) using one-way analysis of variance (ANOVA) by the PROC GLM procedure at 5 % level of significance. Treatment means were separated using the Tukey's Honestly Significant Difference (HSD). The SAS macro pdmix800 was used to perform pairwise comparisons at 5 % level of significance (Saxton, 1998).

## 4.5. Results

### 4.5.1 Soil chemical properties of selected sites

The chemical properties of the upper 40 cm depth of the soil in the selected sites from the Kahama and Shinyanga rural districts are presented in Table 4.1

### 4.5.2. Soil organic carbon storage in whole soil

Soil organic carbon (SOC) content in the 0-100 cm soil depth for the land use systems in the Kahama district ranged from 50.41 Mg C $ha^{-1}$ in reserved ngitili to 67.40 Mg C $ha^{-1}$ in *Melia azedarach* (Fig. 4.1A). The SOC contents in the land use systems in the Kahama district did not show higher difference between the tree-based systems and the farmland. In the Shinyanga rural district, SOC contents in the 0-40 cm depth were higher in the *Leucaena leucocephala* and reserved ngitili compared to the farmland and *Albizia lebbeck* (Fig. 4.1B). Soil organic carbon content to the 40 cm depth ranged from 34.33 Mg C $ha^{-1}$ in farmland to 61.38 Mg C $ha^{-1}$ in *Leucaena leucocephala* (Fig. 4.1B).

**Table 4.1. Soil chemical properties of selected land use systems in the Kahama and Shinyanga rural districts, Tanzania.**

| Depth (cm) | Land use system | pH | Electrical conductivity ($mS\ m^{-1}$) | Available N: $NO_3$-N | Available N: $NH_4$-N | Available P | Exchangeable base cations: K | Ca | Mg | Na |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ---- Mg $kg^{-1}$ ---- | | | | | | |
| | | **Kahama district** | | | | | | | | |
| 0-20 | Reserved ngitili | 5.18bc† | 4.63abc | 2.74ab | 11.24a | 0.77c | 0.21ab | 0.95ab | 0.54a | 0.06b |
| | Degraded ngitili | 4.87c | 5.21abc | 4.77ab | 10.62a | 0.98c | 0.17b | 0.64b | 0.35a | 0.12a |
| | Farmland | 5.20bc | 3.79bc | 1.67b | 8.94a | 7.77a | 0.33ab | 0.69b | 0.54a | 0.06b |
| | Melia azedarach | 6.03a | 7.82abc | 2.66ab | 7.77a | 2.40bc | 0.39a | 0.94ab | 0.45a | 0.09ab |
| | Albizia lebbeck | 5.62ab | 10.55ab | 11.42a | 11.14a | 4.19abc | 0.29ab | 1.05ab | 0.34a | 0.07b |
| | Leucaena leucocephala | 6.19a | 10.67a | 5.10ab | 11.08a | 0.56c | 0.27ab | 1.90a | 0.70a | 0.09ab |
| | Gmelina arborea | 5.05bc | 2.45c | 1.49b | 8.17a | 6.26ab | 0.12b | 0.57b | 0.46a | 0.07b |
| 20-40 | Reserved ngitili | 4.53a | 1.62a | 1.46a | 9.52a | 0.33b | 0.11b | 0.26a | 0.43a | 0.08ab |
| | Degraded ngitili | 4.57a | 3.82a | 3.60a | 7.14a | 0.44b | 0.07b | 0.38a | 0.27a | 0.19a |
| | Farmland | 5.08a | 3.00a | 1.49a | 7.13a | 4.61a | 0.37a | 1.10a | 0.91a | 0.07ab |
| | Melia azedarach | 5.47a | 5.15a | 1.85a | 6.87a | 2.29ab | 0.37a | 0.86a | 0.70a | 0.09ab |
| | Albizia lebbeck | 5.22a | 2.98a | 2.33a | 7.47a | 3.69ab | 0.11b | 0.73a | 0.48a | 0.06b |
| | Leucaena leucocephala | 5.57a | 3.32a | 1.98a | 8.38a | 0.37b | 0.07b | 1.27a | 0.43a | 0.09ab |
| | Gmelina arborea | 4.78a | 1.44a | 1.20a | 7.48a | 2.70ab | 0.09b | 0.86a | 0.60a | 0.06b |
| | | **Shinyanga rural district** | | | | | | | | |
| 0-20 | Reserved ngitili | 6.77a | 42.12a | 4.27a | 19.74a | 0.98a | 0.63a | 14.58a | 3.75a | 1.17a |
| | Farmland | 5.19b | 4.08b | 3.64a | 8.39b | 0.77a | 0.26b | 0.93b | 0.44c | 0.07b |
| | Albizia lebbeck | 5.36b | 3.98b | 2.75a | 11.26b | 0.47a | 0.30b | 1.61b | 0.72bc | 0.07b |
| | Leucaena leucocephala | 5.83b | 7.55b | 5.16a | 8.56b | 0.63a | 0.52ab | 3.99b | 1.20b | 0.10b |
| 20-40 | Reserved ngitili | 7.20a | 46.37a | 2.25a | 17.41a | 0.31b | 0.29a | 15.31a | 3.51a | 2.38a |
| | Farmland | 5.08b | 2.44b | 2.34a | 8.42ab | 0.31b | 0.08b | 1.37b | 0.58c | 0.07b |
| | Albizia lebbeck | 4.98b | 2.98b | 1.38a | 11.05ab | 0.34b | 0.13b | 1.43b | 0.75c | 0.07b |
| | Leucaena leucocephala | 5.17b | 2.34b | 2.29a | 3.95b | 0.80a | 0.19ab | 3.11b | 1.25b | 0.11b |

† Within columns and depth for a district, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD)

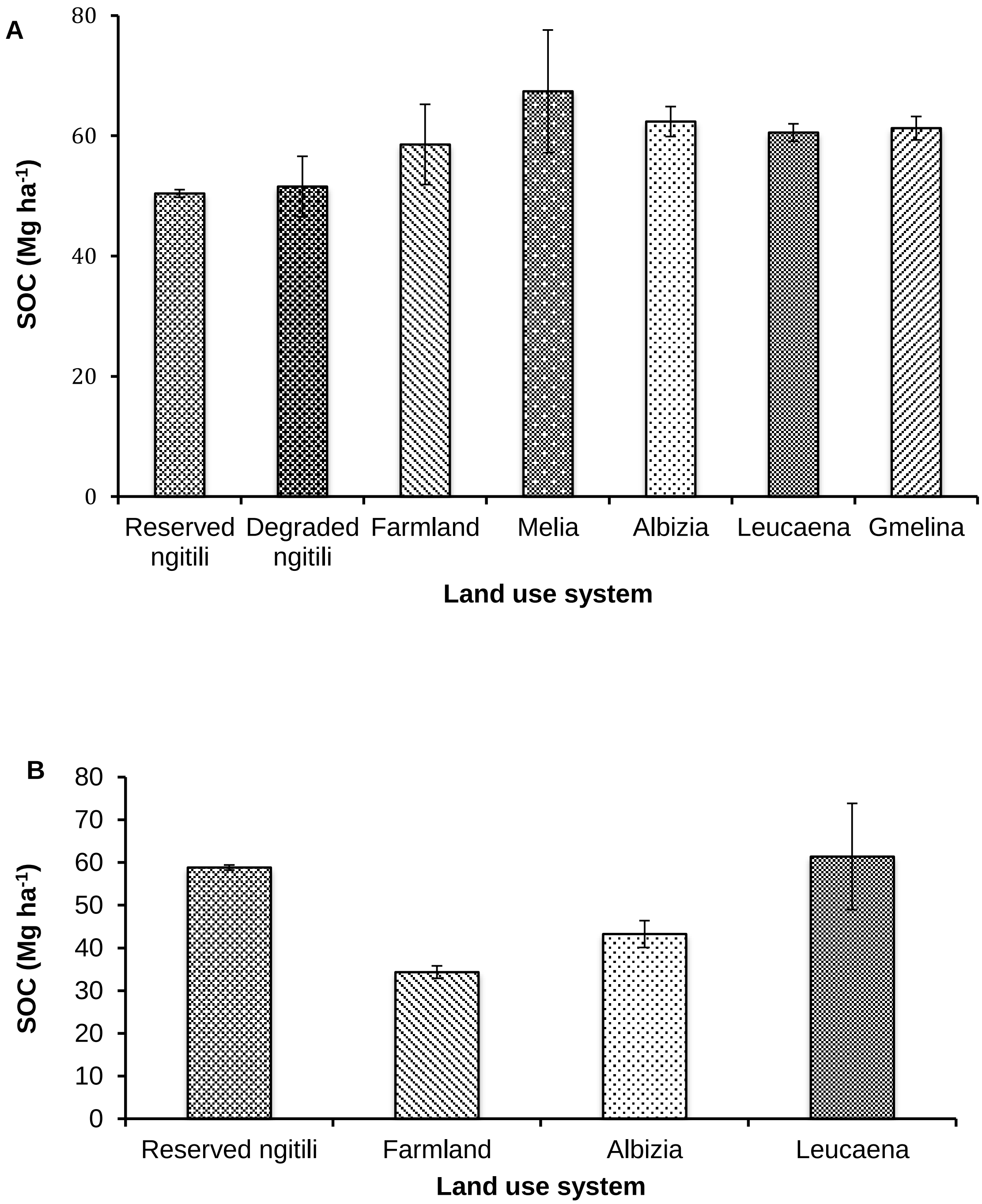


**Fig. 4.1. Soil organic carbon (SOC) content (A) to 100 cm depth in different land uses in the Kahama district and (B) to 40 cm depth in the Shinyanga rural district, Tanzania. Vertical bars indicate standard error of means (n = 3).**

In the Kahama district, *Leucaena leucocephala* had a higher SOC content than the degraded and reserved ngitilis, farmland, and *Melia azedarach* in the 0-20 cm depth class (Table 4.2). At 20-40 cm depth, SOC remained higher in the *Leucaena leucocephala* than the reserved ngitili; however, at the 40-60 cm depth, SOC content was lower in *Leucaena leucocephala* than *Melia azedarach.* The *Leucaena leucocephala* at the 40-60 cm depth did not differ in SOC content compared to the degraded and reserved ngitilis, farmland, *Albizia lebbeck*, and *Gmelina arborea*. Below the 60 cm depth, SOC content did not differ among the land use systems.

Soil organic carbon values generally decreased (significantly) with soil depth in all the land use systems from the Kahama district except in the degraded ngitili and *Melia azedarach* (Table 4.2). Soil organic carbon content in the reserved ngitili was higher in the 0-20 cm depth than the 20-40 cm depth (Table 4.2). Below the 0-20 cm depth class, SOC content in the reserved ngitili did not differ with depth. The farmland had higher SOC content in the 0-20 cm depth than the 40-60 cm depth class and below. Though, SOC in the farmland was 45 % higher in the 0-20 cm than the 20-40 cm depth, this was not statistically different ($p > 0.05$) (Table 4.2). In the *Albizia lebbeck* and *Gmelina arborea* species, similar trend in SOC with depth was observed. For both species, SOC was highest in the 0-20 cm depth. Below the 0-20 cm depth for the *Albizia lebbeck* and *Gmelina arborea*, SOC was only higher in the 20-40 cm than the 80-100 cm depth. The *Leucaena leucocephala* also had its highest SOC content in the 0-20 cm depth followed by the 20-40 cm. Below the 40-60 cm depth; SOC content in the *Leucaena leucocephala* did not differ with depth (Table 4.2).

**Table 4.2. Depthwise distribution of soil organic carbon (SOC) content in Mg C ha$^{-1}$ in the bulk soil up to 100 cm depth for the different land use systems in the Kahama district, Tanzania.**

| Soil depth (cm) | Land use system | | | | | | |
|---|---|---|---|---|---|---|---|
| | Reserved ngitili | Degraded ngitili | Farmland | *Melia azedarach* | *Albizia lebbeck* | *Leucaena leucocephala* | *Gmelina arborea* |
| 0-20 | 19.86a†BC‡ | 13.45a C | 18.35a BC | 19.81a BC | 23.06a AB | 27.82a A | 20.75a AB |
| 20-40 | 7.77b B | 9.91a AB | 12.62ab AB | 13.14a AB | 11.57b AB | 14.45b A | 13.04b AB |
| 40-60 | 8.11b AB | 9.64a AB | 10.02b AB | 13.53a A | 11.37bc AB | 7.27c B | 10.71bc AB |
| 60-80 | 7.46b A | 9.30a A | 8.23b A | 10.80a A | 8.67bc A | 7.29c A | 9.80bc A |
| 80-100 | 7.21b A | 9.26a A | 9.33b A | 10.13a A | 7.70c A | 4.70c A | 6.97c A |

† Within columns, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).

‡ Means in each row for a particular depth class followed by same upper case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).

With regards to the land use systems in the Shinyanga rural district, comparisons of SOC could not be made for depths below 40 and 80 cm for *Albizia lebbeck* and *Leucaena leucocephala*, respectively, (Table 4.3). This was due to the presence of bedrock in the soil profiles, which made it impossible for soil sampling beyond these depths for the two agroforestry species. The SOC content of the different land use systems in this district indicate that with the exception of the 20-40 cm depth class, farmland had lower SOC content at all the depth classes than the reserved ngitili, *Albizia lebbeck*, and *Leucaena leucocephala* (Table 4.3).

Apart from the *Leucaena leucocephala*, which did not differ in SOC content with depth, the reserved ngitili, farmland, and *Albizia lebbeck* land use systems showed differences in SOC content with depth (Table 4.3). In the reserved ngitili, SOC content was higher in the 0-20 cm depth class compared to the 20-40, 40-60, and 60-80 cm depth classes. The 0-20 cm depth class, however, did not differ in SOC content from the 80-100 cm depth class in the reserved ngitili (Table 4.3). The SOC content in the farmland was highest in the 20-40 cm depth class but this amount did not differ from the SOC content in the 0-20 cm depth class. At the 20-40 cm depth class, SOC content in the farmland was higher compared to the 40-60, 60-80, and 80-100 cm depth classes. The 0-20 cm depth on the other hand, differed in SOC content compared to the 60-80, and 80-100 cm depth classes but not the 40-60 cm depth class (Table 4.3). In the *Albizia lebbeck*, SOC was higher in the 0-20 cm than the 20-40 cm depth class.

**Table 4.3. Depthwise distribution of soil organic carbon (SOC) content in Mg C $ha^{-1}$ in the bulk soil up to 100 cm depth for the different land use systems in the Shinyanga rural district, Tanzania.**

| Soil depth (cm) | Land use system | | | |
|---|---|---|---|---|
| | Reserved ngitili | Farmland | *Albizia lebbeck* | *Leucaena leucocephala* |
| 0-20 | 34.06a†A‡ | 16.43ab B | 26.50a AB | 38.58a A |
| 20-40 | 24.77b A | 17.91a A | 16.76b A | 22.80a A |
| 40-60 | 26.01b A | 14.61bc B | ND§ | 24.98a A |
| 60-80 | 26.37b A | 11.48cd B | ND | 20.44a AB |
| 80-100 | 29.62ab A | 11.34d B | ND | ND |

† Within columns, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).
‡ Means in each row for a particular depth class followed by the same upper case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).
§ ND, not determined.

### 4.5.3. Mass distribution of soil aggregate classes

The percentage (%) mass distribution of the soil aggregate classes was different in different land use systems in the Kahama and Shinyanga rural districts (Table 4.4). The ngitili systems and farmlands from the two districts had higher macroaggregates followed by the microaggregates with the silt and clay-aggregates being the lowest. However, higher % of the soil mass was observed in the microaggregates for the planted woodlots, except the *Albizia lebbeck* from the two districts which had higher % mass in the macroaggregates than the microaggregates (Table 4.4).

In the Kahama district, the macroaggregates were higher in the degraded and reserved ngitilis as well as in the farmland than the planted woodlots (Table 4.4). The macroaggregates in the ngitili systems and farmland in this district accounted for more than 45 % of the soil mass at the 0-20 and 20-40 cm depth classes. The macroaggregates in the planted woodlots accounted for less than 45% (Table 4.4). Similarly, the macroaggregates in the 0-20 cm depth for the reserved ngitili and farmland from the Shinyanga rural district constituted more than 45 % of the soil mass compared to the planted woodlots, which had less than 45 %. In the Shinyanga rural district, the % mass of the silt and clay-aggregates was highest in the reserved ngitili than the planted woodlots. This was contrary to observation in the Kahama district where the % mass of silt and clay-aggregates were higher in the planted woodlots than both the reserved and degraded ngitilis (Table 4.4).

### 4.5.4. Soil organic carbon in soil aggregate classes

#### *4.5.4.1. SOC in macroaggregates (2000-250 μm)*

The cumulative value of the SOC (hereafter referred to as "total SOC") for the two depth classes of the macroaggregates within the upper 40 cm soil layer for the Kahama district land use systems were in decreasing order of 12.98 Mg C $ha^{-1}$ (*Melia azedarach*), 12.56 Mg C $ha^{-1}$ (*Leucaena leucocephala*), 11.41 Mg C $ha^{-1}$ (farmland), 9.44 Mg C $ha^{-1}$ (reserved ngitili), 6.93 Mg C $ha^{-1}$ (degraded ngitili), 6.72 Mg C $ha^{-1}$ (*Albizia lebbeck*), and 4.26 Mg C $ha^{-1}$ (*Gmelina arborea*) (Table 4.5). The values for SOC in both depth classes indicate that SOC content in the macroaggregates did not differ with land use change (Table 4.5). With the exception of the reserved ngitili and *Gmelina arborea* where SOC contents were found to be higher in the 0-20 cm depth class than the 20-40 cm depth, SOC content did not differ with depth for the degraded ngitili, farmland, *Melia azedarach*, *Albizia lebbeck*, and *Leucaena leucocephala* (Table 4.5).

**Table 4.4. The percentage (%) mass distribution of the soil aggregate classes in two depth classes under different land use systems in the Kahama and Shinyanga rural districts, Tanzania.**

| Depth (cm) | Size fraction (μm) | Reserved ngitili | Degraded ngitili | Farmland | *Melia azedarach* | *Albizia lebbeck* | *Leucaena leucocephala* | *Gmelina arborea* |
|---|---|---|---|---|---|---|---|---|
| | | ----------------- **Kahama district** ----------------- | | | | | | |
| 0-20 | 2000-250 | 55.50a†A‡ | 46.72a C | 52.15a B | 40.25b E | 43.97a D | 37.66b F | 40.85b E |
| | 250-53 | 33.81b G | 39.52b E | 35.82b F | 44.97a B | 41.91b D | 43.99a C | 45.97a A |
| | <53 | 9.96c F | 12.19c D | 11.12c E | 14.03c B | 13.20c C | 17.15c A | 12.34c D |
| 20-40 | 2000-250 | 55.85a A | 51.09a B | 48.10a C | 37.98b F | 40.22b E | 41.50a D | 42.00b D |
| | 250-53 | 32.59b F | 35.42b E | 38.21b D | 42.64a B | 41.89a B | 40.56b C | 43.62a A |
| | <53 | 11.05c F | 12.49c E | 12.80c D | 17.65c A | 16.88c B | 16.83c B | 13.79c C |
| | | ----------------- **Shinyanga rural district** ----------------- | | | | | | |
| 0-20 | 2000-250 | 51.26a A | ND§ | 47.99a B | ND | 43.20a C | 35.16b D | ND |
| | 250-53 | 24.84b D | ND | 32.88b C | ND | 39.17b B | 44.25a A | ND |
| | <53 | 22.29c A | ND | 18.20c C | ND | 16.82c D | 19.87c B | ND |
| 20-40 | 2000-250 | 41.63a B | ND | 44.76a C | ND | 44.76a A | 31.56b C | ND |
| | 250-53 | 29.90b D | ND | 35.77b C | ND | 37.93b B | 46.63a A | ND |
| | <53 | 26.73c A | ND | 18.81c A | ND | 16.65c D | 20.29c B | ND |

† Within columns and depth for a district, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).

‡ Means in each row and fraction size for a district followed by the same upper case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).

§ ND, not determined

On the part of the Shinyanga rural district land use systems, total SOC in the macroaggregates within the upper 40 cm soil layer were in decreasing order of 30.60 Mg C ha$^{-1}$ (reserved ngitili), 12.8 Mg C ha$^{-1}$ (*Leucaena leucocephala*), 9.27 Mg C ha$^{-1}$ (farmland), and 8.69 Mg C ha$^{-1}$ (*Albizia lebbeck*) (Table 4.5). In both depth classes, the reserved ngitili had higher SOC content in the macroaggregates than the farmland and *Albizia lebbeck* (Table 4.5). Soil organic carbon content in the reserved ngitili was higher than the *Leucaena leucocephala* in the 20-40 cm depth class but did not differ in the 0-20 cm depth class. In the 20-40 cm depth class, the *Leucaena leucocephala* had more SOC content than the farmland and *Albizia lebbeck*. Soil organic carbon content was higher in the 0-20 cm depth class than the 20-40 cm depth class for all the Shinyanga rural district land use systems, except the farmland, which did not differ in SOC with depth (Table 4.5).

**Table 4.5. Total soil organic carbon (SOC) (Mg C ha$^{-1}$) in macroaggregates (2000-250 µm) at two different depths in different land use systems from the Kahama and Shinyanga rural districts, Tanzania.**

| Depth (cm) | Reserved ngitili | Degraded ngitili | Farmland | *Melia azedarach* | *Albizia lebbeck* | *Leucaena leucocephala* | *Gmelina arborea* |
|---|---|---|---|---|---|---|---|
| | **Kahama district** | | | | | | |
| 0-20 | 7.21a†A‡ | 3.35a A | 8.90a A | 8.54a A | 4.22a A | 8.48a A | 2.71a A |
| 20-40 | 2.23b A | 3.58a A | 2.51a A | 4.44a A | 2.50a A | 4.08a A | 1.55b A |
| | **Shinyanga rural district** | | | | | | |
| 0-20 | 19.97a A | ND§ | 7.13a B | ND | 5.82a B | 7.54a AB | ND |
| 20-40 | 10.63b A | ND | 2.14a C | ND | 2.87b C | 5.26b B | ND |

† Within columns for a district, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).
‡ Means in each row and depth for a district followed by the same upper case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).
§ ND, not determined

### *4.5.4.2. SOC in microaggregates (250-53 μm)*

The total SOC in the microaggregates within the 40 cm soil depth were in decreasing order of 18.56 Mg C $ha^{-1}$ (*Melia azedarach*), 18.19 Mg C $ha^{-1}$ (*Leucaena leucocephala*), 16.57 Mg C $ha^{-1}$ (farmland), 11.36 Mg C $ha^{-1}$ (reserved ngitili), 11.16 Mg C $ha^{-1}$ (*Gmelina arborea*), 10.57 Mg C $ha^{-1}$ (*Albizia lebbeck*), and 8.40 Mg C $ha^{-1}$ (degraded ngitili) (Table 4.6). Similar to the SOC content in the macroaggregates, SOC in the microaggregates did not differ with land use change in both depth classes (Table 4.6). The reserved ngitili, *Albizia lebbeck*, and *Gmelina arborea* had more SOC content in the 0-20 cm depth than the 20-40 cm depth class in the microaggregates. The other systems did not differ in SOC content with depth.

Within the 40 cm soil depth, the total SOC of the microaggregates for the land use systems in the Shinyanga rural district were in decreasing order of 37.02 Mg C $ha^{-1}$ (*Leucaena leucocephala*), 21.91 Mg C $ha^{-1}$ (*Albizia lebbeck*), 18.96 Mg C $ha^{-1}$ (reserved ngitili), and 13.32 Mg C $ha^{-1}$ (farmland) (Table 4.6). In the 0-20 cm depth class, the SOC content in the microaggregates for the Shinyanga rural district land use systems was highest in *Leucaena leucocephala*, followed by *Albizia lebbeck*, reserved ngitili, and farmland. Soil organic carbon in the 20-40 cm depth class remained higher in the *Leucaena lecocephala* than the other land use systems in the Shinyanga rural district. The reserved ngitili, farmland, and *Albizia lebbeck* did not differ in SOC content in the 20-40 cm depth class. The SOC content in the microaggregate for the reserved ngitili and *Albizia lebbeck* did not differ with depth. Conversely, SOC was higher in the 20-40 cm depth class than the 0-20 cm depth for farmland and the *Leucaena leucocephala* had higher SOC in the 0-20 cm than 20-40 cm depth (Table 4.6).

**Table 4.6. Total soil organic carbon (SOC) (Mg C ha$^{-1}$) in microaggregates (250-53 µm) at two different depths in different land use systems from the Kahama and Shinyanga rural districts, Tanzania.**

| Depth (cm) | Reserved ngitili | Degraded ngitili | Farmland | Melia azedarach | Albizia lebbeck | Leucaena leucocephala | Gmelina arborea |
|---|---|---|---|---|---|---|---|
| | ------ **Kahama district** ------ | | | | | | |
| 0-20 | 8.93a†A‡ | 5.17a A | 9.29a A | 12.98a A | 7.09a A | 13.46a A | 6.62a A |
| 20-40 | 2.43b A | 3.23a A | 7.28a A | 5.58a A | 3.48b A | 4.73a A | 4.54b A |
| | ------ **Shinyanga rural district** ------ | | | | | | |
| 0-20 | 9.48a C | ND§ | 5.78b D | ND | 12.48a B | 23.44a A | ND |
| 20-40 | 9.48a B | ND | 7.54a B | ND | 9.43a B | 13.58b A | ND |

† Within columns for a district, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).
‡ Means in each row and depth for a district followed by the same upper case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).
§ ND, not determined

#### *4.5.4.3. SOC in silt and clay sized aggregates (<53 µm)*

The total SOC of the silt and clay sized aggregates within the 40 cm soil depth for the Kahama district land use systems were in decreasing order of 16.01 Mg C ha$^{-1}$ (*Leucaena leucocephala*), 11.64 Mg C ha$^{-1}$ (*Melia azedarach*), 10.56 Mg C ha$^{-1}$ (*Albizia lebbeck*), 9.96 Mg C ha$^{-1}$ (reserved ngitili), 9.89 Mg C ha$^{-1}$ (*Gmelina arborea*), 9.27 Mg C ha$^{-1}$ (farmland), 9.17 Mg C ha$^{-1}$ (degraded ngitili) (Table 4.7). In the 0-20 cm depth class, apart from the *Leucaena leucocephala*, which had the highest SOC content, all the other systems did not differ in SOC content in this depth class. Soil organic carbon content in the 20-40 cm depth class remained higher in *Leucaena leucocephala* than the degraded and reserved ngitilis and farmland. The SOC content in the two ngitilis, farmland, *Melia azedarach*, *Albizia lebbeck,* and *Gmelina arborea* did not differ from each other in the 20-40 cm depth class. With the exception of the *Gmelina arborea,* which did not differ in SOC with depth, SOC in all the Kahama district land use systems were higher in the 0-20 cm depth class than the 20-40 cm depth in the silt and clay fraction (Table 4.7).

The total SOC of the silt and clay sized aggregates for the Shinyanga rural district land use systems were in decreasing order of 21.06 Mg C $ha^{-1}$ (*Leucaena leucocephala*), 19.45 Mg C $ha^{-1}$ (reserved ngitili), 17.64 Mg C $ha^{-1}$ (farmland), and 14.89 Mg C $ha^{-1}$ (*Albizia lebbeck*) (Table 4.7). Similar to the Kahama district land use systems, it was only the *Leucaena leucocephala* in the Shinyanga rural district, which had a higher SOC content in the 0-20 cm depth class. All the other systems in the Shinyanga rural district did not differ in SOC content in the 0-20 cm depth. In the 20-40 cm depth class, the *Albizia lebbeck* had lower SOC content than the reserved ngitili but did not differ in SOC content compared to the farmland and *Leucaena leucocephala*. Soil organic carbon content did not differ with depth in the farmland and *Albizia lebbeck*; however, the reserved ngitili had more SOC in the 20-40 cm than the 0-20 cm depth class. Soil organic carbon in the *Leucaena leucocephala* was higher in the 0-20 cm than the 20-40 cm depth class (Table 4.7).

**Table 4.7. Total soil organic carbon (SOC) (Mg C ha$^{-1}$) in silt and clay fraction (<53 µm) at two different depths in different land use systems from the Kahama and Shinyanga rural districts, Tanzania.**

| Depth (cm) | Reserved ngitili | Degraded ngitili | Farmland | Melia azedarach | Albizia lebbeck | Leucaena leucocephala | Gmelina arborea |
|---|---|---|---|---|---|---|---|
| | | | **Kahama district** | | | | |
| 0-20 | 6.70a†B‡ | 5.77a B | 5.66a B | 6.70a B | 6.41a B | 10.30a A | 5.51a B |
| 20-40 | 3.26b B | 3.40b B | 3.61b B | 4.94b AB | 4.15b AB | 5.71b A | 4.38a AB |
| | | | **Shinyanga rural district** | | | | |
| 0-20 | 7.52b B | ND§ | 8.18a B | ND | 9.78a B | 14.12a A | ND |
| 20-40 | 11.93a A | ND | 9.46a AB | ND | 5.11a B | 6.94b AB | ND |

† Within columns for a district, means followed by the same lower case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).

‡ Means in each row and depth for a district followed by the same upper case letters are not significantly different ($p > 0.05$) according to the Tukey's Honestly Significant Difference (HSD).

§ ND, not determined

### 4.5.5. Carbon K-edge spectroscopy

Results for the XANES C K-edge spectra was only considered for the silt and clay sized aggregates in the 20 cm depth for the land use in the Kahama district. The C K-edge spectra for the other samples could not be considered due to poor signal to noise of the spectra generated. The poor signals of the C K-edge spectra from these samples could be attributed to the low SOC contents in these samples, which could have been below the detection limits of the beamline at the time of the data collection. The different C types in the silt and clay sized aggregates for the Kahama land use systems for the 20 cm depth were identified using the resonances from the spectra. Resonances corresponding to different C types have been identified as unsaturated C (284.5 eV), aromatic C (285 eV), pyridinic-C (285.5), ketone (286.8 eV), phenolic (287.1 eV), carboxylic (288.6 eV), carbohydrate hydroxyl (289.6 eV), and carbonate (290.5 eV) (Gillespie et al., 2011, 2014). The C K-edge spectra for the silt and clay-sized soil aggregates for the land use systems in the Kahama district (Fig. 4.2) showed the presence of aromatic (feature 2) and carboxylic (feature 4) as the common features in all the five land use systems. All but the *Leucaena leucocephala* showed presence of unsaturated C (feature 1). Although, carbohydrate C (feature 5) was observed in all the land use systems, its presence was less obvious in the woodlots and reserved ngitili compared to the degraded ngitili and farmland. Signals of the C K-edge spectra again showed presence of ketones (feature 3) in the ngitilis and farmland but not in the woodlots.

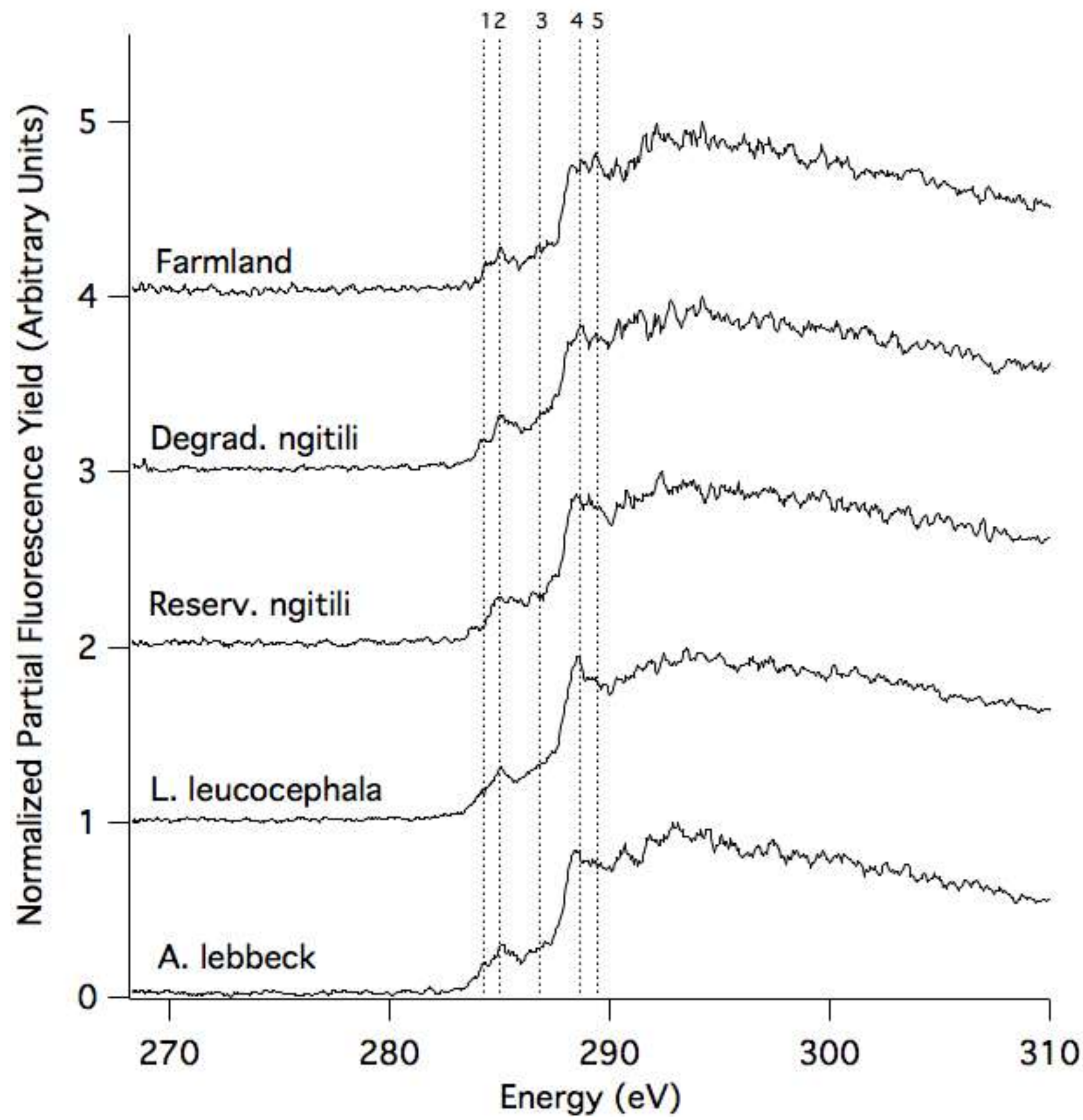


**Fig. 4.2. Normalized Absorbance (partial fluorescence yield) C K-edge XANES spectra of silt and clay sized aggregate soils in the upper 20 cm depth under different land use systems in the Kahama district in Tanzania. Resonances corresponding to C types are shown as: feature 1 (unsaturated C at 284.5 eV); 2 (aromatic C at 285 eV); 3 (ketone at 286.8 eV); 4 (carboxylic at 288.6 eV); and 5 (carbohydrate hydroxyl at 289.6 eV).**

### 4.6. Discussion

#### 4.6.1. Soil organic carbon in whole soil

Tree-based systems such as agroforestry systems and forests have been associated with higher SOC storage compared to treeless systems, indicating higher C sequestration potential of agroforestry systems. However, the rate of SOC build-up in agroforestry systems differs with tree species, management practices, and the environmental factors within which the system is located (Nair et al., 2010). Saha et al. (2010) indicated that SOC in agroforestry systems in semiarid and arid regions is lower than in humid regions. Information on the soil C sequestration potentials of the woodlot systems in the dry semiarid region of northwestern Tanzania are unexplored. This study evaluated the soil C sequestration potential of some selected woodlot species and ngitili systems in the Shinyanga region.

Unexpectedly, SOC stocks in the ngitilis and planted woodlots of *Melia azedarach*, *Albizia lebbeck*, *Leucaena leucocephala*, and *Gmelina arborea* in the Kahama district did not differ from the farmland. This observation contradict most findings in SOC studies where soil cultivation has been observed to induce SOC loss. For example, Walker and Desanker (2004) reported a 40 % loss of SOC in agricultural soils compared to natural miombo woodlands in Malawi. Solomon et al. (2000) also observed a 56 % decrease in SOC after 15 years of cultivating a native tropical woodland in northern Tanzania. After a 5-year fallow period, Kimaro et al. (2011) observed 21.6-25.6 Mg C $ha^{-1}$ SOC in the top 0-15 cm in *Acacia* woodlots compared to 13 Mg C $ha^{-1}$ in continuously cropped land in Morogoro, Tanzania. The loss of SOC as a result of cultivation has been attributed to low input of organic matter and losses due to erosion, mineralization, and leaching (Lugo and Brown, 1993). Nevertheless, the nature of SOC changes induced by cultivation has been indicated to be dependent on the soil management practice (Christensen, 1992). The addition of organic residue on farmlands enhances SOC accumulation (Duiker and Lal, 1999). Sanchez et al. (1983) indicated that with proper management, agricultural soils in the tropics could retain or recover lost organic matter. As reported by a majority of the farmers in the studied districts, the use of rice bran as a source of manure on farmland is a common practice to improve crop yield due to the high cost of chemical fertilizers. Therefore, the similar levels of SOC stocks in the ngitili and woodlot systems compared to the farmland in the Kahama district suggests that, SOC from crop residue that might have been left on the farmland after each cycle of crop harvest and the application of rice bran was enough to maintain SOC levels in the farmland similar to those in the ngitili and woodlot systems.

Dry miombo woodlands in the semiarid regions have also been identified to have slow rate of SOC accumulation (Williams et al., 2008). After two decades of regrowth of a miombo woodland, Williams et al. (2008) did not observe a change in SOC stocks with period of regrowth. This led the authors to suggest that the dry miombo woodlands have a very slow rate of SOC accumulation. Solomon et al. (2000) also noted no significant change in SOC to 0.1 m depth in native and degraded miombo woodlands in northern Tanzania. The slow rate of SOC accumulation in dry miombo woodlands could be explained by the increased rate of SOM decomposition in tropical soils as a result of high temperatures (Six et al., 2002b). Soil organic carbon accumulation is a function of organic matter input and losses from organic matter decomposition. The accumulation of SOC is enhanced when inputs are in excess of losses (Janzen, 2004). The slow rate of

SOM accumulation in tropical soils and for that matter soils from the miombo region as observed by Williams et al. (2008) could explain why SOC in the tree-based systems in the Kahama district were not higher than the farmland. It was therefore not surprising that after 20 years of being under reserve, SOC stocks in the reserved ngitili (miombo woodland) from the Kahama district did not differ from the degraded ngitili (miombo woodland) in our study.

Also, as sandy soils tend to accumulate less SOC than clay soils (Lugo and Brown, 1993), the slow SOC accumulation rate in soils in the Kahama district by the tree-based systems could be attributed to the high percentage of sand in the soils (Appendix Table B.3.). As was observed in the Shinyanga rural district, both the *Leucaena leucocephala* and reserved ngitili had higher clay contents than the *Albizia lebbeck* and farmland in this district. Soil organic carbon has been shown to increase with increased clay contents (Jobbagy and Jackson, 2000). Therefore, the higher SOC contents in the *Leucaena leucocephala* and reserved ngitili than the farmland and *Albizia lebbeck* in the Shinyanga rural district could be a reflection of the higher clay contents. Conversely, the high amount of sand in the soils under the land use systems in the Kahama district could suggest the lack of SOC improvement in the ngitili and woodlot systems from the Kahama district relative to the farmland.

Again, in the northern part of Tanzania, the establishment of woodlots on infertile patches of land is a common practice (Luedeling et al., 2011). The potential of a tree-based system in SOC storage is influenced by the previous history of the land use system (Lugo and Brown, 1993). Therefore, in instances where the woodlots were established on degraded sites for purposes of land restoration, as was the case for the Kahama district woodlots (except the young *Gmelina arborea*), SOC build-up under the woodlots would be expected to be slow. There is also the possibility of farmers selecting areas with 'richer' soils for cultivation. This means that the retention of crop residue and addition of rice bran to these 'richer' cultivated soils decreases the likelihood of high SOC depletion in the farmlands to levels lower than those in the planted woodlots established on infertile soils.

Kimaro et al. (2014) observed that, despite the higher SOC stocks in *Acacia auriculiformis*, and *Acacia crassicarpa* woodlot species than farmland, SOC stocks in *Acacia mangium* did not differ from the farmland. In another study, Kimaro et al. (2011) did not observe higher SOC stocks to 0.15 m depth in *Gliricidia sepium* woodlot compared to a continuous cropped land. These findings indicate that the ability of an agroforestry system to store higher SOC than a treeless system is also dependent on the agroforestry species. Lugo and Brown (1993) explained that SOC accumulation differs with the tree species as some species produce more litter or roots than others. Since none of the woodlot species from the Kahama district had higher SOC stocks than the farmland, it indicates that the woodlot species considered in this study have a slow rate of SOC accumulation in sandy soils.

### 4.6.2. Depth effect on SOC distribution in whole soil

The higher SOC stocks in the uppermost 20 cm depth compared to the lower soil depths was due to the build-up of organic matter from plant litter in the topsoil. In tree-based systems, aboveground inputs from trees have been indicated to be more important in SOC accumulation than belowground root turnover (Guo and Gifford, 2002). Despite observing the highest SOC stocks in the 20 cm depth layers in the tree-based systems, less than 50 % of the SOC stocks relative to the total SOC stocks in the whole soil profile (up to 1 m) were found in the 20 cm depth in all the land use systems from both districts. Kimaro et al. (2014) found that over 50 % of the total SOC stocks to 1.2 m depth in *Acacia* woodlots and native woodlands in Tanzania was within the 20 cm depth. In a review of the vertical distribution of SOC, Jobbagy and Jackson (2000) revealed the existence of a strong effect of plant functional type (vegetation) on the vertical distribution of SOC. Within a given climate, SOC was indicated to be deeper in shrublands, followed by grasslands, and forests, with 50 % of SOC to 1 m depth in forests located in the uppermost 20 cm depth. The lower percent of SOC stocks in the uppermost 20 cm depth in the land use systems could be attributed to the loss of SOC in the surface soils. The loss of SOC in the upper layers of coarse soil fractions through leaching is documented (Jobbagy and Jackson, 2000). Therefore, in sandy soils like those in the study sites leaching may have accounted for the loss of SOC in the surface soils, hence the lower percent of SOC in the uppermost 20 cm depth. Below the 60 cm depth, the vertical distribution of SOC in each of the land use systems from the two districts was uniform. A meta-analysis on the effect of land use change on SOC stocks revealed that the conversion of forest to cropland significantly reduced SOC to a 60 cm depth, but beyond the 60 cm depth the conversion had no influence on the SOC stocks (Guo and Gifford, 2002). Kimaro et al. (2014) also explained that the effect of vegetation on SOC change was confined to the upper soil layers and that, SOC in subsoils are less altered by the vegetation type. This explains why SOC was uniform beyond the 60 cm depth in all the land use systems from the two districts.

With regards to difference in SOC stocks in the ngitilis and woodlots relative to the farmland at the various depths in the Kahama district, the slow rate of SOC build-up in the woodlots and ngitili systems as indicated earlier could have accounted for the lack of discernible improvement in SOC in these tree-based systems relative to the farmland at the various depths in the Kahama district. In the Shinyanga rural district, however, the tree-based systems showed significant improvement in SOC in the various depths compared to the farmland. The higher SOC in the tree-based systems than the farmland at the various depths could be due to the higher clay contents in the tree-based systems, especially in the *Leucaena leucocephala* and reserved ngitili than the farmland (Appendix Table B.4). Within a given climate, SOC has been revealed to increase with increased clay contents (Jobbagy and Jackson, 2000).

#### 4.6.3. Distribution of soil aggregates and soil organic carbon in soil aggregates

Aggregates are secondary particles formed through the combination of mineral particles with organic and inorganic binding agents (Tisdall and Oades, 1982). Soil aggregates are classified into macroaggregates (250-2000 μm diameter), microaggregates (53-250 μm diameter), and silt and clay fractions (<53 μm) depending on diameter (Nair et al., 2010). Tree-based systems improve soil aggregation and the formation of macroaggregates due to increased organic matter input (Bronick and Lal, 2005). Saha et al. (2010) reported higher percent macroaggregates in forest soils compared to soil under rice paddy fields. Different from our expectation in this study, the percentage mass distribution of the various soil aggregate classes in the different land use systems showed relative abundance of microaggregates than macroaggregates in the woodlot systems from the Kahama and Shinyanga rural districts. This implies that SOM input from the woodlots had little impact on macroaggregates formation as higher macroaggregates were observed in the farmland. It could therefore, be argued that binding agents other than SOM were responsible for the formation of macroaggregates. This is because, if SOM were responsible for the formation of the macroaggregates, the woodlots would have had more macroaggregates than the farmland. In oxide-rich soils, oxides have been indicated to dominate as binding agents and the impact of SOM in the formation of macroaggregates in such soils is less (Oades and Waters, 1991). The presence of red color in highly weathered tropical soils suggests the presence of iron oxides (Walker 1974). Therefore, in red soils as those in the study sites, oxides are likely to be present. The likely presence of iron oxides in these soils suggests that they might be responsible for the formation of the macroaggregates resulting in SOM having a lesser impact on the formation of macroaggregates. This could explain the observed lower mass percent of macroaggregates under the woodlot systems.

Regarding the SOC distribution in the various aggregate classes, SOC contents in the macroaggregates were not higher than SOC in the small aggregates despite findings in other studies reporting the contrary. Gama-Rodrigues et al. (2010) observed that 72, 20, and 8 % of SOC in cacao agroforestry system in Brazil were contained in macroaggregates, microaggregates, and silt and clay fractions, respectively. Kimaro et al. (2014) also observed that SOC in macroaggregates were about two times greater than SOC in microaggregates and silt and clay fractions. However, Gama-Rodrigues et al. (2011) indicated that when oxides rather than SOM are responsible for macroaggregates formation, macroaggregates would not be expected to contain high C contents compared to microaggregates. It was therefore, not surprising that SOC contents in the macroaggregates were not higher than those in the microaggregates and silt and clay fractions as macroaggregates in the soils in our study sites were believed to be formed by oxides. Rather, the planted woodlots had higher SOC stocks to the 40 cm depth in the small aggregate classes compared to the macroaggregates.

Comparison of SOC in the various aggregate classes between the different land use systems also showed that SOC was higher only in the small aggregate classes under the woodlots than the farmland and ngitili systems. Other than the reserved ngitili from the Shinyanga rural district, SOC in the macroaggregates did not differ between the land use systems. It has been revealed that SOC in the macroaggregates are more susceptible to degradation and losses compared to SOC in microaggregates and silt and clay fractions (Nair et al., 2010). This is because macroaggregates contain the recent C depositions in soil and are more sensitive to changes in SOM dynamics with time (Nair et al., 2010) compared to SOM in smaller aggregates, which are stabilized through the formation of organo-mineral complexes (Six et al., 2002). Hence, the lack of observable differences in SOC in the macroaggregates between the land use systems could be attributed to SOC loss in this aggregate class to levels where a change in SOC across all the land use systems became less apparent. In tropical soils, increased SOM decomposition rate have been documented (Six et al., 2002b). The increased rate of SOM decomposition in tropical soils has been linked to high temperatures in these regions, which results in the rapid depletion of SOM causing slow organic matter accumulation in these soils (Six et al., 2002b). The slow rate of SOM accumulation in tropical soils could also be a contributing factor to the inability of the tree-based systems in this study to accumulate higher SOC in the macroaggregates compared to the farmland. The association of higher amount of the SOC in the woodlots with microaggregates and silt and clay fractions suggest that majority of the SOC under the woodlots are more stabilized compared to those in the farmland and ngitili systems. This is due to the ability of microaggregates and silt and clay fractions to form organo-mineral complexes from the interactions of clay minerals and humic substances.

#### 4.6.4. Comparison of SOC stocks between the Kahama and Shinyanga rural districts

The comparison of SOC stocks in the land use systems between the two districts generally showed higher SOC stocks in the Shinyanga rural districts than the Kahama district. In the Shinyanga rural district, the reserved ngitili, farmland, *Albizia lebbeck*, and *Leucaena leucocephala* land use systems had 53 %, 8 %, 20 %, and 31 % more SOC stocks to 40 cm depth than the corresponding land use systems in the Kahama district. Although, it was expected that SOC in the Kahama district would be higher than the Shinyanga rural district owing to the relatively wetter condition in the Kahama district than the Shinyanga rural district, the higher percentage of clay in the land use systems in the Shinyanga rural district relative to the Kahama district contributed to the storage of SOC. The ability of clay minerals to stabilize SOC by forming organomineral complexes with SOM reduces decomposition rate (Six et al., 2002). This implies that despite the high biomass production in the wetter district, the ability of the system to accumulate SOC was more influenced by clay. Jobbagy and Jackson (2000) explained an increase in SOC with increased clay contents. Feller et al. (2001) argues that within latitudinal gradients, SOC stocks will be very dependent on the soil mineralogy and soil texture.

Therefore, higher clay contents in the soils under the land use systems in the Shinyanga rural district than the Kahama district could explain why in spite of the wetter conditions in the Kahama district, SOC was rather higher in the land use systems in the Shinyanga rural district.

#### 4.6.5. Influence of land use change on SOM chemistry as revealed by the C K-edge spectroscopy

The bioavailability of SOC has been linked to the chemical composition of the soil organic matter (Krull et al., 2003). Soil organic matter is more susceptible to biodegradation when the organic material dominates in labile fractions (von Lutzow et al., 2006). Carbohydrates and carboxylic compounds are found in plants and microbial biomass (Gillespie et al., 2014). The origination of these compounds from plants and microbial source could explain their presence in all the land use types. However, Gillespie et al. (2014) indicated that these organic compounds are labile and so more susceptible to decomposition. Stabilization of labile SOC compounds in silt and clay sized aggregates have been reported (Solomon et al., 2000). Silt and clay soil aggregates stabilize SOC through the formation of organo-mineral complexes (Six et al., 2002). Owing to their susceptibility to degradation, carbohydrates and carboxylic C compounds in soils are expected to be short-lived. Whereas the presence of the aromatic C compounds in the Kahama district land use systems could be attributed to their recalcitrance to decomposition (Helfrich et al., 2006), the presence of the labile carbohydrates and carboxylic C compounds could be assigned to the stabilization offered to these C compounds by the silt and clay soil aggregates (Solomon et al., 2000).

Ketones in soils have been identified as products resulting from microbial metabolism of aromatic compounds (Gillespie et al., 2014). The presence of aromatic compounds in farmland and ngitilis therefore, does not make the observed presence of ketones surprising. Although, aromatic compounds are indicated to be recalcitrant, the observation that the soil biota community is capable of decomposing any organic matter of natural origin (von Lutzow et al., 2006) makes it understandable that decomposition of aromatic compounds in these land use systems resulted in the accumulation of the ketones. Silt and clay sized aggregates are known to be associated with stable C. Therefore the suggestion that SOM decomposition occurred in the silt and clay sized aggregates in the ngitili and farmland means that prolonged SOM degradation in sites with slow rate of organic matter accumulation will result in degradation of organo-mineral stabilized C. This could be expected in soils of tropical climates due to high rate of organic matter degradation as a result of high temperatures. Solomon et al. (2000) observed that clearing and cultivation of a native tropical woodland in northern Tanzania resulted in a decline in SOM contents in all soil size fractions, confirming the observation in this study that SOM degradation occurred in silt and clay sized aggregates.

Despite the woodlots showing presence of aromatic compounds, ketones were observed to be absent. The continuous addition of organic matter from the woodlots might have resulted in making available more labile compounds such as carbohydrates and carboxylic in the woodlots. The availability of more of these labile substrate of carbohydrate and carboxylic could have resulted in them being the more preferred substrate for decomposition and this could be the reason why ketones were not observed in the woodlot sites. The preference of carbohydrate as substrate for degradation in the woodlot could also explain the less conspicuous carbohydrates signals observed for both woodlot species as most of them might have been decomposed.

## 4.7. Conclusion

Generally, SOC stocks in the whole soil did not differ with a change in land use system in the Kahama district. In the Shinyanga rural district, however, higher SOC stocks were observed in the reserved ngitili and *Leucaena leucocephala* due to high clay contents in these land uses compared to the *Albizia lebbeck* and farmland. Soil organic carbon was observed to decrease with depth; nonetheless, less than 50 % of the total SOC to a meter depth was contained in the uppermost 20 cm layer. Due to the absence of baseline SOC stocks for the studied land use systems and a time-sequence study involving long time intervals, the soil C values reported in this study indicate the carbon sequestration potential of the systems. The C sequestration potential of the woodlots of *Melia azedarach*, *Albizia lebbeck*, *Leucaena leucocephala*, and *Gmelina arborea* ranged from 60.54-67.40 Mg C $ha^{-1}$ to 1 m depth in the Kahama district and 43.26 and 61.38 Mg C $ha^{-1}$ to 0.4 m depth in *Albizia lebbeck* and *Leucaena leucocephala* in the Shinyanga rural district. The inability of the planted woodlots to store SOC higher than the farmland, particularly in the Kahama district could also be attributed to their establishment on sites that were degraded. This means that the assessment of SOC storage potential of agroforestry and other tree-based systems relative to other land uses must always take into consideration the previous land history. The lack of a discernable increase in SOC in the tree-based systems also shows the slow SOC accumulation rate in the dry miombo region. This slow rate of SOC accumulation in these soils is contributed by an increased rate of SOM degradation and high content of sand in the soil. The mass distribution of the soil aggregates demonstrated abundance of microaggregates in the woodlots and macroaggregates in the farmland, suggesting that organic matter inputs from the woodlot systems had little impact on the formation of macroaggregates. This suggests that binding agents such as oxides rather than SOM were responsible for the formation of the macroaggregates. As a result, SOC was observed to be generally higher in the microaggregates compared to the macroaggregates, especially in the woodlot systems. The association of higher SOC stocks under the woodlot systems with the microaggregates and silt and clay fractions than the farmland reflect high stability of SOC in the woodlot systems. Between the two districts, SOC stocks in the land use systems in the Shinyanga rural district were higher than in the Kahama district despite the wetter conditions in the latter district. The higher stocks of SOC in the Shinyanga rural district was attributed to the high clay contents compared to the Kahama district.

Moreover, the C K-edge XANES spectra for the silt and clay sized aggregates in the upper 20 cm soil depth layer for the land use systems from the Kahama district showed the presence of both labile and recalcitrant SOC compounds. The presence of ketones in the farmland and ngitili sites shows evidence of microbial degradation of recalcitrant SOM such as aromatic compounds in this aggregate size. Although, aromatic compounds were present in the woodlots, the absence of ketones in the woodlots points to the understanding that aromatic compounds may have been preserved in the woodlots. The continuous addition of litter in the woodlots appeared to have preserved the aromatic pools. The preservation of aromatic compounds in the woodlots and the degradation of these recalcitrant compounds in the farmland and ngitilis indicate the ability woodlot species such as *Albizia lebbeck* and *Leucaena leucocephala* have in storing more recalcitrant C in the silt and clay sized aggregates, hence contributing to long-term SOC stabilization in the silt and clay sized aggregates.

# 5. SYNTHESIS AND CONCLUSIONS

Agroforestry systems are known to play important role in atmospheric C sequestration (Nair et al., 2010). The carbon sequestration potential of a particular system depends on the environmental conditions, the species involved in the system and the system management (Albrecht and Kandji, 2003). Rotational woodlot is an agroforestry technology comprising of sole stands of fast growing trees that are planted on farms and degraded lands for fuelwood, timber, and land restoration (Nyandzi et al., 2003). These woodlots hold high promise to reduce forest degradation and offset carbon dioxide ($CO_2$) emissions mainly through on-farm wood production for fuelwood and charcoal supply and other related uses (Kimaro et al., 2011). Besides these woodlot systems, ngitili systems in the Shinyanga region are also believed to hold high promise in biomass and soil C sequestration.

Aboveground biomass (AGB) estimation is an essential aspect of biomass carbon studies (Mani and Parthasarathy, 2007). Generalized biomass equations have been developed for different forest types and tree species. The use of regression models for biomass estimation relies on tree growth parameters such as total height and tree diameter (Vashum and Jayakumar, 2012). Despite the considerable attention the woodlots and ngitili systems in the Shinyanga region have received on their carbon sequestration potentials, biomass C pools are lacking for the majority of these woodlot species and ngitili systems. In addition to the lack of biomass C pools in these woodlots, SOC stocks have less been studied in these systems. The amount of C sequestered in the soil is influenced by the quantity and quality of the organic matter input as well as the properties of the soil such as soil structure and their aggregations (Nair et al., 2010). Therefore, knowledge about the form and location of the soil C is needed for a better understanding of the turnover rates of the C pools within the soil and to allow better evaluation of the C sequestration potential of these woodlot and ngitili systems in Shinyanga region in northwestern Tanzania.

The general aim of this research was to estimate the biomass and soil C pools in woodlots, ngitili systems and farmlands in the Shinyanga region and the influence of these land use systems on the SOM chemistry. Biomass C pools were estimated using developed equations from the literature. Soil organic carbon stocks in whole soil and different soil aggregates were also studied. Additionally, synchrotron-based C K-edge XANES spectroscopy technique was used to evaluate the chemistry of the SOM as influenced by the different land use systems in the soil aggregates.

## 5.1. Summary of findings

*Melia azedarach*, *Albizia lebbeck*, *Leucaena leucocephala*, and *Gmelina arborea* have widely been used as agroforestry tree species in the Shinyanga region in Tanzania; however, little research has been done to determine the biomass and soil C sequestration potential in these agroforestry species from this region. Estimates of the biomass C stocks in these woodlots compare well with those studied in other regions. The aboveground biomass carbon (AGBC) (24.40 Mg C ha$^{-1}$) and the total biomass carbon (TBC) (30.74 Mg C ha$^{-1}$) for the *Albizia lebbeck* in the Kahama district in this study were close to the 26.87 Mg C ha$^{-1}$ (AGBC) and 33.85 Mg C ha$^{-1}$ (TBC) reported by Chavan and Rasal (2012). The estimated 43.11 Mg ha$^{-1}$ aboveground biomass (AGB) for *Gmelina arborea* in this study is in the reported range of 11-364 Mg ha$^{-1}$ (Banaticla et al., 2007) and close to the estimated 43.9 Mg ha$^{-1}$ in a similar age *Gmelina arborea* plantation in India (Swamy et al., 2003). However, the AGBC estimates for the *Leucaena leucocephala* in this study (21.01 and 23.57 Mg C ha$^{-1}$ for Kahama district and Shinyanga rural district, respectively) were slightly lower than the 32 Mg C ha$^{-1}$ reported by Albrecht and Kandji (2003). On the other hand, the total biomass of 29.64 Mg ha$^{-1}$ estimated in this study for *Melia azedarach* is lower than the 21.1 Mg ha$^{-1}$ reported by Roy et al. (2006). Based on the age of woodlot stands, *Gmelina arborea* had the highest CSP rates (3.59 Mg C ha$^{-1}$ year$^{-1}$) compared to the *Albizia lebbeck* (1.44 Mg C ha$^{-1}$ year$^{-1}$), *Leucaena leucocephala* (1.24 Mg C ha$^{-1}$ year$^{-1}$), and *Melia azedarach* (0.69 Mg C ha$^{-1}$ year$^{-1}$). The AGBC stock (22.46 Mg C ha$^{-1}$) for the reserved ngitili (a miombo woodland) was also similar to the 22.5 Mg C ha$^{-1}$ reported by Zahabu et al. (2008) and also within the range reported in other miombo woodlands by Shirima et al. (2011) and Madoffe et al. (2012). Biomass C stocks in the degraded ngitili (miombo woodland) reduced by 15.11 Mg C ha$^{-1}$.

Another objective of the research was to evaluate SOC stocks in whole soil and different soil aggregates in the woodlots, ngitili systems, and farmland and to also assess the impacts these land use systems have on the different forms of C stored in soil aggregates. Soil organic carbon stocks in the whole soil to 1 m depth in the Kahama district ranged from 50.41 to 67.40 Mg C ha$^{-1}$ whereas to 0.4 m depth, SOC in the Shinyanga rural district ranged from 34.33 to 61.38 Mg C ha$^{-1}$. Due to the absence of baseline SOC stocks for the studied land use systems and a time-sequence study involving long time intervals, the soil C values reported in this study indicate the carbon sequestration potential of the systems. The woodlot and ngitili systems in the Kahama district did not improve SOC stocks than the farmland suggesting slow rate of SOC accumulation in these sites. On the contrary, higher SOC stocks were observed in the reserved ngitili and *Leucaena leucocephala* in the Shinyanga rural district due to high clay contents in these land uses compared to the *Albizia lebbeck* and farmland. Despite the lack of increased SOC stocks in the tree-based systems in the soil aggregates compared to the farmland, SOC under the woodlots were more associated with the microaggregates and silt and clay sized aggregates reflecting the stability of SOC in the woodlot systems. Similar to the SOC stocks in the soil aggregates, organic matter inputs from the woodlots did not improve macroaggregation compared to the farmland suggesting that the influence of organic matter in macroaggregate formation was less.

Also, the C K-edge XANES spectra revealed the degradation of recalcitrant aromatic compounds in farmland and the ngitilis as evidenced by the presence of ketones. The continuous addition of litter in the woodlots appeared to have preserved the aromatic pools indicating the ability the woodlots have in storing more recalcitrant C in the silt and clay sized aggregates. This study demonstrates the significant contributions of woodlots to accumulate biomass and soil C stocks and the capability of these woodlots to offset $CO_2$ emissions through the long-term stabilization of SOC in the soil aggregates.

## 5.2. Future research

Cutting and weighing tree biomass in the field is regarded as the most accurate method to estimate aboveground tree biomass (Ketterings et al., 2001; Kaonga and Bayliss-Smith, 2009). However, this procedure restrict its use to small areas and small tree sample sizes due to the complexity and labour intensiveness involved (Ketterings et al., 2001; Delitti et al., 2006; Kaonga and Bayliss-Smith, 2009). As a result, regression models that relate biomass growth parameters such as total tree height and basal diameter have often been used to estimate biomass and biomass C pools. Owing to differences in architecture and wood density of different tree species, the use of species-specific equations is preferred in developing allometric equations for accurate biomass C estimation (Ketterings et al., 2001). In this study, since the biomass models were adopted from the literature, future studies of these woodlots should include destructively sampled trees to validate the models used for the biomass estimations in this study.

Also, considering that C sequestration is a rate process and requires time sequence studies to quantify its extent (Saha et al., 2010), further studies will be required in these land use systems to give a better understanding of the rate of C change with time, as this will contribute to our understanding of the C sequestration rates in these systems. Soil organic carbon studies in the land use systems should in the future consider soil depths beyond the 1 m depth considered in this study. This is because most soils have been reported to store 37 to 39 % of their total SOC to a 2 m depth between the 1 and 2 m depth (Lorenz and Lal, 2005). Moreover, SOC studies in soil aggregates should look beyond the 40 cm depth as used in this study since SOC stabilization with clay contents is also observed to increase with increased soil depth. This will broaden our understanding on the impacts soils in this region have in offsetting global $CO_2$ emissions and how the different land use systems influence SOC stabilization and sequestration. Finally, to ascertain that oxides rather SOM was responsible for macroaggregation in these red tropical soils for which reason higher SOC stocks were not observed in macroaggregates than the smaller aggregate classes, future studies in these soils should investigate the processes which dominate in aggregate formation in these soils.

## 6. REFERENCES


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# APPENDIX A

**Table A.1. Local and botanical names of the tree species sampled from the reserved and degraded ngitili systems in the Kahama district, Tanzania.**

| Local name | Botanical name |
|---|---|
| Mkalya | *Zanha africana* |
| Mfubata | *Diosypros fischeri* |
| Mtobo | *Azanza garckeana* |
| Munaradura | *Lannea schweinfurthii* |
| Mtundu | *Brachystegia spiciformis* |
| Mmale | *Lonchocarpus cupassa* |
| Msima | *Terminalia sericea* |
| Msana | *Combretum zeyheri* |
| Ng'ochangoko | *Catunaregum taylorii* |
| Mgumo | *Ficus stuhimanni* |
| Msungululu | *Strophanthus eminii* |
| Mtundum | *Dichrostachys cinerea* |
| Mlama | *Combretum molle* |
| Mmerambasa | *Dalbergia nitidula* |
| Msalasi | *Friesodielsia obovata* |
| Mdati | *Kigeria africana* |
| Mnene | *Flacourtia indica* |
| Nujaminzi | *Combretum fragrans* |
| Mgando | *Burkea africana* |
| Mkola | *Afzelia quanzensis* |
| Bukwata | *Acacia mellifera* |
| Mbelembe | *Albizia gummifera* |
| Mpaba | *Markchamia obtusifolia* |
| Mkonola | *Annona senegalensis* |
| Mtumbi | *Gercinia livingstone* |
| Mninga | *Pterocarpus angolensis* |
| Mkwaju | *Tamarindus indica* |
| Mpandepande | *Strychnos heterodoxa* |
| Nago | *Berchemia discolor* |
| Mtundwa | *Ximenia americana* |
| Mgagati | *Abrus precatorius* |
| Mbale | *Lonchocarpus bussei* |
| Munugwanhal**o** | *Allophylus griso-tomentosus* |
| Milujamizi | *Combretum adenogunium* |
| Mbelebele | *Diplorhynchus condylocarpon* |
| Msanzambeke | *Crossopteryx febrifuga* |
| Mselya | *Lannea fulva* |
| Mpala | *Hymenocadia acida* |
| Mwininga chini | *Pterocarpus angolensis* |
| *Mbuyu* | *Adansonia digitata* |

# APPENDIX B

**Table B.1. Summarized data for soil bulk density, % SOC and SOC stocks as measured in soils from the different land use systems in the Kahama district, Northwestern Tanzania.**

| Land use | Depth (cm) | Mean bulk density ($Mg\ m^{-3}$) | Mean SOC (%) | Mean SOC stocks ($Mg\ ha^{-1}$) |
|---|---|---|---|---|
| Reserved ngitili | 0-20 | 1.41 ± 0.037 | 0.71 ± 0.014 | 19.86 ± 0.900 |
| | 20-40 | 1.45 ± 0.005 | 0.27 ± 0.025 | 7.77 ± 0.736 |
| | 40-60 | 1.47 ± 0.049 | 0.28 ± 0.009 | 8.11 ± 0.006 |
| | 60-80 | 1.49 ± 0.024 | 0.25 ± 0.018 | 7.46 ± 0.647 |
| | 80-100 | 1.51 ± 0.082 | 0.24 ± 0.033 | 7.21 ± 1.379 |
| Degraded ngitili | 0-20 | 1.38 ± 0.016 | 0.49 ± 0.057 | 13.45 ± 1.405 |
| | 20-40 | 1.42 ± 0.005 | 0.35 ± 0.034 | 9.91 ± 0.980 |
| | 40-60 | 1.38 ± 0.029 | 0.35 ± 0.033 | 9.64 ± 0.716 |
| | 60-80 | 1.59 ± 0.069 | 0.29 ± 0.088 | 9.30 ± 3.194 |
| | 80-100 | 1.53 ± 0.005 | 0.30 ± 0.072 | 9.26 ± 2.225 |
| Farmland | 0-20 | 1.61 ± 0.180 | 0.58 ± 0.107 | 18.35 ± 1.695 |
| | 20-40 | 1.52 ± 0.165 | 0.41 ± 0.085 | 12.62 ± 3.754 |
| | 40-60 | 1.38 ± 0.079 | 0.36 ± 0.062 | 10.02 ± 1.804 |
| | 60-80 | 1.46 ± 0.156 | 0.28 ± 0.061 | 8.23 ± 2.421 |
| | 80-100 | 1.59 ± 0.065 | 0.29 ± 0.016 | 9.33 ± 0.116 |
| *Melia azedarach* | 0-20 | 1.59 ± 0.043 | 0.62 ± 0.114 | 19.81 ± 3.954 |
| | 20-40 | 1.47 ± 0.054 | 0.45 ± 0.126 | 13.14 ± 3.237 |
| | 40-60 | 1.43 ± 0.045 | 0.48 ± 0.132 | 13.53 ± 3.734 |
| | 60-80 | 1.51 ± 0.000 | 0.36 ± 0.096 | 10.80 ± 2.890 |
| | 80-100 | 1.46 ± 0.000 | 0.35 ± 0.033 | 10.13 ± 0.968 |
| *Albizia lebbeck* | 0-20 | 1.54 ± 0.045 | 0.75 ± 0.074 | 23.06 ±1.717 |
| | 20-40 | 1.41 ± 0.114 | 0.41 ± 0.036 | 11.57 ± 0.441 |
| | 40-60 | 1.52 ± 0.065 | 0.38 ± 0.048 | 11.37 ± 0.994 |
| | 60-80 | 1.45 ± 0.146 | 0.30 ± 0.018 | 8.67 ± 1.373 |
| | 80-100 | 1.50 ± 0.071 | 0.26 ± 0.011 | 7.70 ± 0.476 |
| *Leucaena leucocephala* | 0-20 | 1.47 ± 0.102 | 0.92 ± 0.049 | 26.82 ± 0.451 |
| | 20-40 | 1.36 ± 0.009 | 0.53 ± 0.026 | 14.45 ± 0.712 |
| | 40-60 | 1.40 ± 0.005 | 0.26 ± 0.035 | 7.27 ± 0.956 |
| | 60-80 | 1.53 ± 0.016 | 0.24 ± 0.045 | 7.29 ± 1.463 |
| | 80-100 | 1.60 ± 0.159 | 0.15 ± 0.008 | 4.70 ± 0.720 |
| *Gmelina arborea* | 0-20 | 1.53 ± 0.016 | 0.68 ± 0.013 | 20.75 ± 0.623 |
| | 20-40 | 1.52 ± 0.021 | 0.43 ± 0.011 | 13.04 ± 0.155 |
| | 40-60 | 1.53 ± 0.045 | 0.35 ± 0.011 | 10.71 ± 0.024 |
| | 60-80 | 1.53 ± 0.057 | 0.32 ± 0.015 | 9.80 ± 0.824 |
| | 80-100 | 1.53 ± 0.016 | 0.23 ± 0.101 | 6.97 ± 3.157 |

**Table B.2. Summary of soil bulk density and % SOC as measured in soils from the different land use systems and agroforestry tree species in the Shinyanga rural district, Northwestern Tanzania.**

| Land use | Depth (cm) | Mean bulk density ($Mg\ m^{-3}$) | Mean SOC (%) | Mean SOC stocks ($Mg\ ha^{-1}$) |
|---|---|---|---|---|
| | 0-20 | 1.40 ± 0.033 | 1.22 ± 0.084 | 34.06 ± 1.564 |
| | 20-40 | 1.55 ± 0.098 | 0.80 ± 0.028 | 24.77 ± 0.703 |
| Reserved ngitili | 40-60 | 1.74 ± 0.061 | 0.75 ± 0.063 | 26.01 ± 3.102 |
| | 60-80 | 1.70 ± 0.008 | 0.78 ± 0.021 | 26.37 ± 0.573 |
| | 80-100 | 1.71 ± 0.005 | 0.86 ± 0.057 | 29.62 ± 1.939 |
| | 0-20 | 1.51 ± 0.123 | 0.54 ± 0.031 | 16.43 ± 1.892 |
| | 20-40 | 1.52 ± 0.062 | 0.59 ± 0.018 | 17.91 ± 0.200 |
| Farmland | 40-60 | 1.47 ± 0.059 | 0.50 ± 0.031 | 14.61 ± 0.482 |
| | 60-80 | 1.44 ± 0.045 | 0.40 ± 0.021 | 11.48 ± 0.964 |
| | 80-100 | 1.47 ± 0.071 | 0.39 ± 0.015 | 11.34 ± 0.192 |
| *Albizia lebbeck* | 0-20 | 1.53 ± 0.070 | 0.86 ± 0.087 | 26.50 ± 3.857 |
| | 20-40 | 1.36 ± 0.125 | 0.62 ± 0.031 | 16.76 ± 0.757 |
| *Leucaena leucocephala* | 0-20 | 1.48 ± 0.168 | 1.36 ± 0.483 | 38.58 ± 9.734 |
| | 20-40 | 1.24 ± 0.144 | 0.96 ± 0.456 | 22.80 ± 9.225 |
| | 40-60 | 1.28 ± 0.024 | 0.98 ± 0.098 | 24.98 ± 2.027 |
| | 60-80 | 1.24 ± 0.049 | 0.82 ± 0.177 | 20.44 ± 5.183 |

**Table B.3. The percentage of the various soil particle sizes and the textural classes of the land use systems from the Kahama district, Tanzania.**

| Land use system | Depth | Sand | Silt | Clay | Textural class |
|---|---|---|---|---|---|
| | cm | ---------------------% | | ------------------- | |
| Reserved ngitili | 0-20 | 80.3 | 8.4 | 11.3 | |
| | 20-40 | 75.3 | 9.4 | 15.3 | |
| | 40-60 | 77.5 | 5.0 | 17.5 | Sandy loam |
| | 60-80 | 76.0 | 5.9 | 18.1 | |
| | 80-100 | 75.6 | 6.0 | 18.4 | |
| Degraded ngitili | 0-20 | 81.1 | 7.7 | 11.2 | |
| | 20-40 | 78.7 | 9.2 | 12.1 | |
| | 40-60 | 71.6 | 6.1 | 22.3 | Sandy loam |
| | 60-80 | 61.8 | 15.5 | 22.7 | |
| | 80-100 | 60.8 | 17.2 | 22.0 | |
| Farmland | 0-20 | 76.4 | 10.4 | 13.2 | |
| | 20-40 | 68.6 | 8.8 | 22.6 | |
| | 40-60 | 68.8 | 3.0 | 28.2 | Sandy clay loam |
| | 60-80 | 64.6 | 5.0 | 30.4 | |
| | 80-100 | 62.6 | 8.4 | 29.0 | |
| Agroforestry species | | | | | |
| *Melia azedarach* | 0-20 | 76.1 | 14.7 | 9.2 | |
| | 20-40 | 70.1 | 9.0 | 20.9 | |
| | 40-60 | 65.0 | 8.7 | 26.3 | Sandy loam |
| | 60-80 | 63.4 | 9.1 | 27.5 | |
| | 80-100 | 68.4 | 14.1 | 17.5 | |
| *Albizia lebbeck* | 0-20 | 74.4 | 12.3 | 13.3 | |
| | 20-40 | 68.1 | 9.6 | 22.3 | |
| | 40-60 | 67.6 | 7.5 | 24.9 | Sandy clay loam |
| | 60-80 | 66.5 | 10.2 | 23.3 | |
| | 80-100 | 70.5 | 8.3 | 21.2 | |
| *Leucaena leucocephala* | 0-20 | 79.5 | 7.7 | 12.8 | |
| | 20-40 | 75.3 | 9.4 | 15.3 | |
| | 40-60 | 79.6 | 5.8 | 14.6 | Sandy loam |
| | 60-80 | 80.2 | 4.7 | 15.1 | |
| | 80-100 | 75.9 | 9.7 | 14.4 | |
| *Gmelina arborea* | 0-20 | 79.1 | 7.2 | 13.7 | |
| | 20-40 | 74.9 | 4.9 | 20.2 | |
| | 40-60 | 69.3 | 6.1 | 24.6 | Sandy clay loam |
| | 60-80 | 68.1 | 6.0 | 25.9 | |
| | 80-100 | 67.3 | 8.9 | 23.8 | |

**Table B.4. The percentage of the various soil particle sizes and the textural classes of the land use systems from the Shinyanga rural district, Tanzania.**

| Land use system | Depth cm | Sand | Silt | Clay | Textural class |
|---|---|---|---|---|---|
| | | ---------------------- | % | -------------------- | |
| Reserved ngitili | 0-20 | 24.9 | 23.4 | 51.7 | |
| | 20-40 | 22.4 | 26.1 | 51.5 | |
| | 40-60 | 23.1 | 25.1 | 51.8 | Clay |
| | 60-80 | 21.6 | 26.7 | 51.7 | |
| | 80-100 | 20.4 | 24.9 | 54.7 | |
| Farmland | 0-20 | 73.0 | 8.9 | 18.1 | |
| | 20-40 | 57.4 | 12.6 | 30.0 | |
| | 40-60 | 56.4 | 6.6 | 37.0 | Sandy clay loam |
| | 60-80 | 56.0 | 9.2 | 34.8 | |
| | 80-100 | 55.4 | 12.5 | 32.1 | |
| Agroforestry species | | | | | |
| Albizia lebbeck | 0-20 | 63.4 | 12.4 | 24.2 | |
| | 20-40 | 52.2 | 13.7 | 34.1 | Sandy clay loam |
| Leucaena leucocephala | 0-20 | 49.9 | 18.8 | 31.3 | |
| | 20-40 | 29.4 | 27.2 | 43.4 | Clay |
| | 40-60 | 21.2 | 32.4 | 46.4 | |
| | 60-80 | 28.1 | 24.5 | 47.4 | |

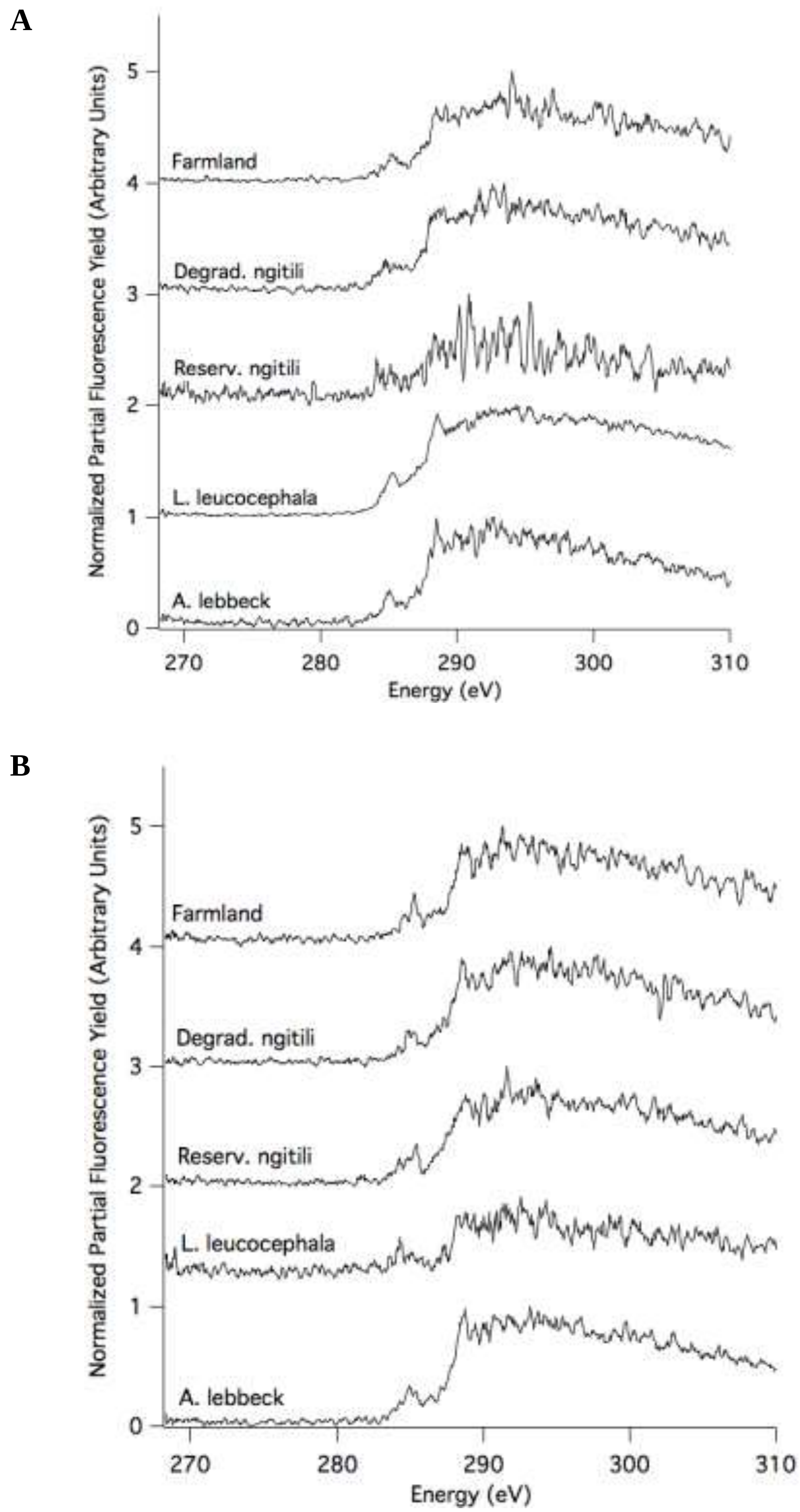



**Fig. B.1. Normalized Absorbance (partial fluorescence yield) C K-edge XANES spectra of the soil macroaggregates in (A) 20 cm depth and (B) 40 cm depth under different land use systems in the Kahama district in Tanzania.**

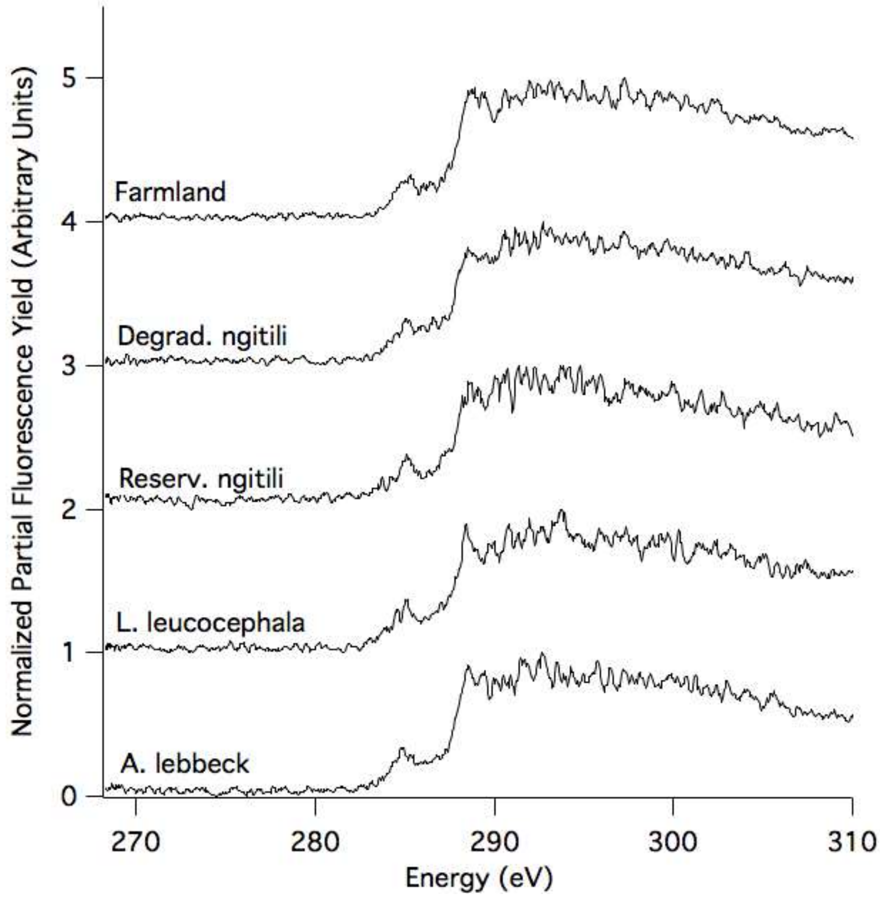



**Fig. B.2. Normalized Absorbance (partial fluorescence yield) C K-edge XANES spectra of silt and clay sized aggregate soils in the 40 cm depth under different land use systems in the Kahama district in Tanzania.**

A

B

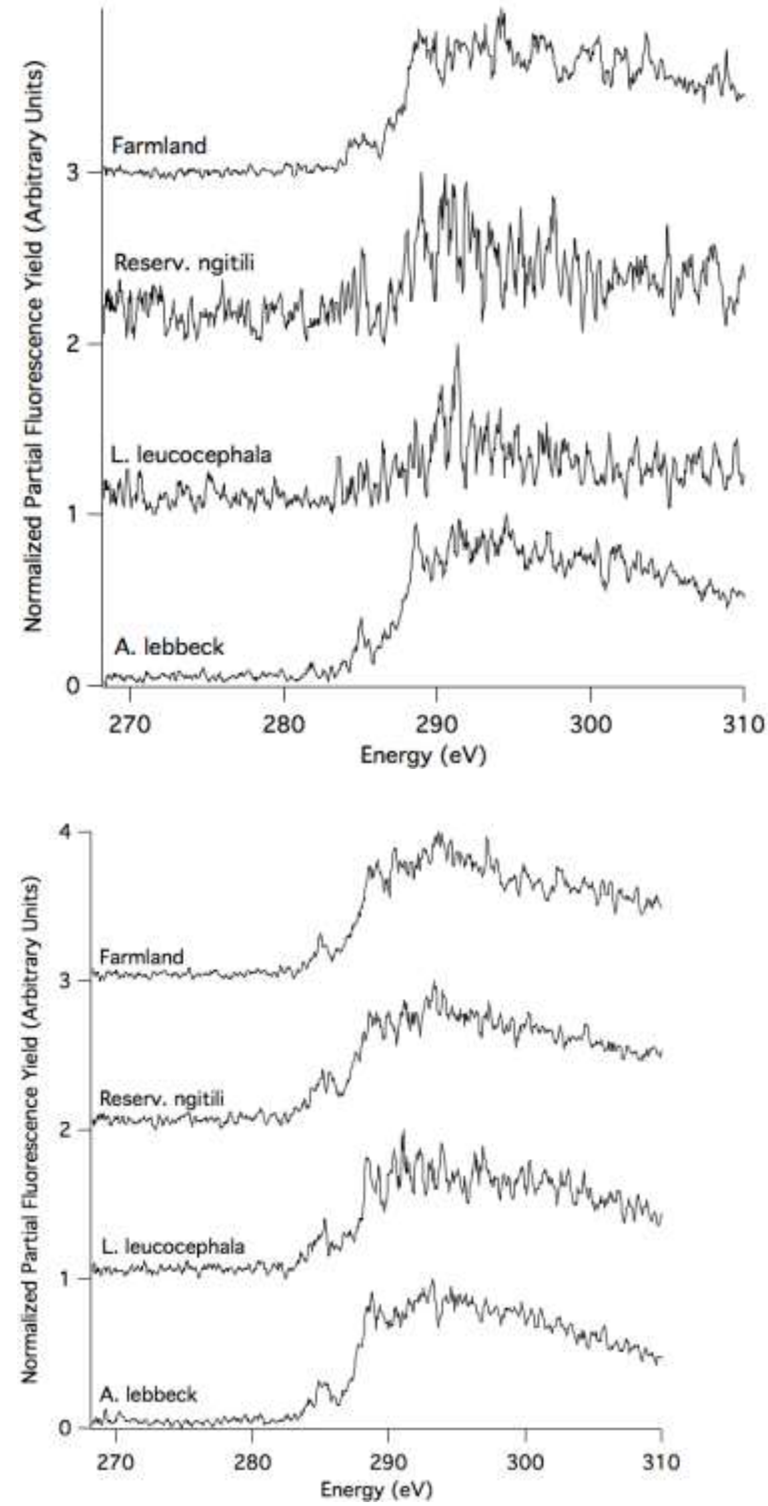
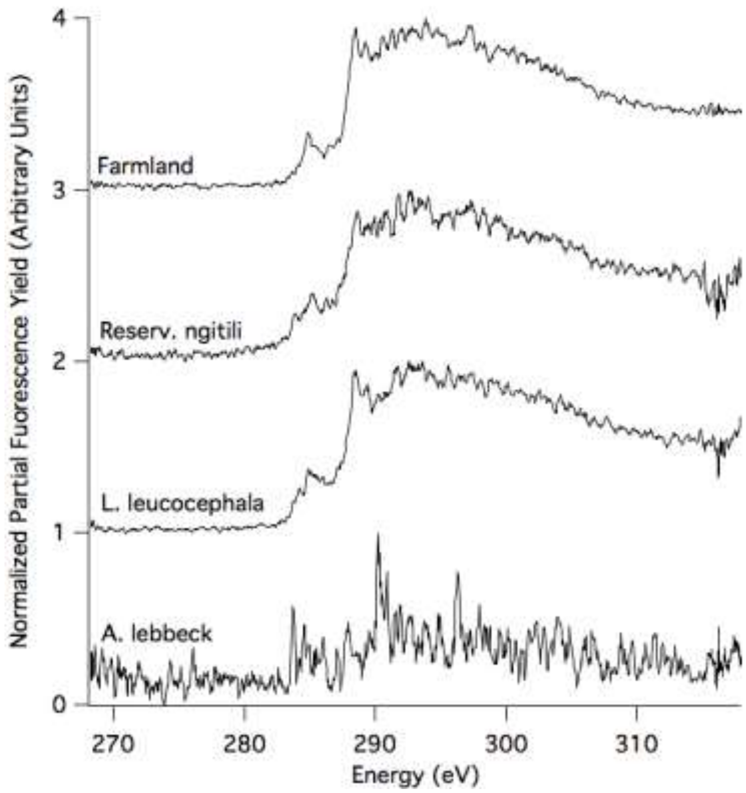



**Fig. B.3. Normalized Absorbance (partial fluorescence yield) C K-edge XANES spectra of the soil macroaggregates in (A) 20 cm depth and (B) 40 cm depth under different land use systems in the Shinyanga rural district in Tanzania.**

A




B

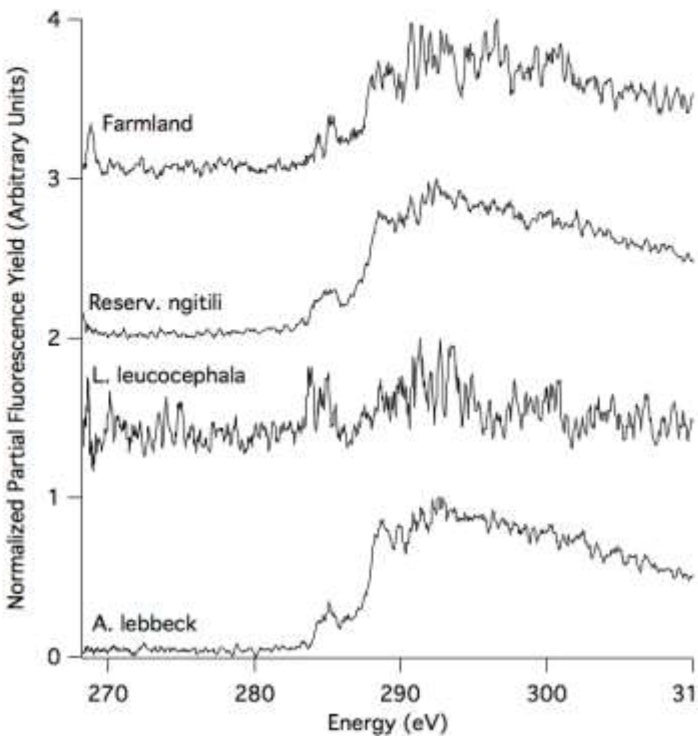



**Fig. B.4. Normalized Absorbance (partial fluorescence yield) C K-edge XANES spectra of the silt and clay sized soil aggregates in (A) 20 cm depth and (B) 40 cm depth under different land use systems in the Shinyanga rural district in Tanzania.**

**Fig. B.5. Soil profile pit showing the red soil colour in the studied land use systems**